THE MINERALOGICAL MAGAZINE

AND

JOURNAL OF
THE MINERALOGICAL SOCIETY

No. 206 September, 1949 Vol. XXVIII

The petrology of the evaporites of the Eskdale no. 2 boring, east Yorkshire.

PART I. *The lower evaporite bed.*

(With Plates XXIX–XXXIV.)

By F. H. STEWART, B.Sc., Ph.D., F.G.S.

Department of Geology, Science Laboratories, Durham, University of Durham.

[Read March 31, 1949.]

CONTENTS

I. Introduction and acknowledgements 622
II. Material examined ... 623
III. General succession in the lower evaporite bed ... 625
IV. The minerals:
(1) Anhydrite 626
(2) Celestine 627
(3) Dolomite 628
(4) Gypsum 628
(5) Halite 629
(6) Magnesite 630
(7) Polyhalite 631
(8) Pyrite 632
(9) Quartz... 632
(10) Native Sulphur ... 632
(11) Talc 633
V. Halite-anhydrite-rocks ... 633
VI. Anhydrite-carbonate-rocks:
(1) Anhydrite-dolomite-rock 637
(2) Brecciated anhydrite-dolomite-rock ... 639
(3) Anhydrite-dolomite-rock with coarse fibro-radiate anhydrite ... 641
(4) Compact anhydrite-magnesite-rock ... 642
(5) Coarse anhydrite-magnesite-halite-rock ... 643
(6) Anhydrite-magnesite-halite-talc-rock ... 643
(7) Anhydrite-dolomite-magnesite-rock ... 645
VII. Polyhalite-bearing rocks:
(1) Halite-anhydrite-polyhalite-talc-rock ... 648
(2) Development of polyhalite in compact anhydrite-dolomite-rock... 651
(3) Polyhalite-bearing rocks with pseudomorphous structure after gypsum ... 652
(4) Rocks consisting almost entirely of polyhalite 655
(5) Anhydrite porphyroblasts in polyhalite-bearing rocks ... 656
(6) Chemical composition 656
VIII. Origin of the polyhalite-bearing rocks 657
IX. The relation between magnesite and dolomite ... 663
X. The distribution and origin of talc 665
XI. Summary and conclusions 669
List of references 672

I. INTRODUCTION AND ACKNOWLEDGEMENTS.

IN 1938–39 the D'Arcy Exploration Company, Limited, sank a borehole (Eskdale well no. 2) to a depth of 5040 feet near Aislaby, Eskdale, Yorkshire, to test the oil or gas possibilities in the Permian Magnesian Limestone. As the well was some distance from any previous boring through the Permian salt series, the Company undertook to carry out continuous coring through this series in the public interest. The boring passed through Lias, Rhaetic, and Trias, and finished in the Permian Lower Magnesian Limestone. The geological results of this boring have been discussed by Lees and Taitt (1945), and fig. 1 has been reproduced from their paper. It can be seen that three evaporite beds were passed through; two in the Upper Permian salt zone, and one in the Middle Permian.

The evaporites consist mainly of halite and anhydrite. In 1942 Tilley exhibited a core specimen of polyhalite, from a depth of about 4500 feet, to the Mineralogical Society (Tilley, 1943). Lees and Taitt (1945) show a 45-foot bed of massive polyhalite in their section (fig. 1) in the lower evaporite bed, and mention a thin zone of sylvinite at the top of the middle evaporite bed. Guppy (1944) has recorded boracite in well cuttings from the middle evaporite bed.

The writer visited the site of the boring in 1942 and collected a number of core samples, many of which consisted largely of polyhalite. He was employed by Imperial Chemical Industries, Limited, at the time, and drew this to their attention, and found that the D'Arcy Exploration Company had arranged with I.C.I. that the latter should undertake chemical analyses and examination of the cores of the boring. The Imperial Chemical Industries had therefore taken core samples from the boring while it was being put down, and by chemical analysis they had found potassium present in considerable quantity in parts of the upper and middle evaporite beds and in one sample from the lower evaporite bed. Sylvine had been found in the upper part of the middle evaporite bed. Since then the writer has examined the available specimens petrologically, together with well cuttings supplied by the D'Arcy Exploration Company, and other minerals of potassium-bearing evaporites have been found (notably carnallite and rinneite in the upper evaporites). Talc has been found as a significant constituent of the upper and lower evaporite beds. The rocks show evidence of many interesting replacement changes since their original deposition.

A petrographic account of the lower evaporites (4313–4773 feet below

surface) is presented in this paper. The upper evaporites will be described in a later communication.

Some of the work was done at the I.C.I. Research Laboratories, Billingham-on-Tees, and it has been continued at Durham University. I should like to express my sincere thanks to Imperial Chemical Industries and the D'Arcy Exploration Company for supplying material for examination; to Durham Colleges for a research grant to defray expenses; to Dr. F. A. Bannister for his X-ray examination of a specimen of talc from this boring; and to Mr. G. O'Neill for taking the photographs which illustrate this paper.

II. MATERIAL EXAMINED.

Core samples of known depth.—These were collected by I.C.I. while drilling was in progress. A considerable number of core samples were taken from the upper evaporite beds, which consist largely of chlorides. Only eleven samples, however, were taken from the lower evaporite bed, which consists largely of sulphates. The presence of polyhalite in considerable quantity was not realized at the time.

The eleven samples preserved consist of pieces of core, 2–4 inches in length, from the following depths: 4312–14, 4314–16, 4350–52, 4352–54, 4356–58, 4415, 4445–47, 4491–93, 4559–61, 4742, 4760–62 feet below surface.

Core samples of unknown depth.—A considerable number of core samples was collected by the writer at the site of the boring in 1942. These had been lying in the open since the boring was completed in 1939, and the more soluble salts had been dissolved away. These specimens, therefore, consist largely of anhydrite with carbonates, although a considerable amount of polyhalite has been preserved within weathered crusts of secondary gypsum in certain specimens.

The exact depth of these specimens is unknown, but since the diameter of the core from the lower evaporite bed was $2\frac{1}{2}$ inches, and of that from the upper evaporites $4\frac{1}{2}$ inches, it is possible to separate the specimens of the lower bed from the others. Since so few samples of known depth have been preserved, these specimens have given valuable information on the petrology of this bed.

Well cuttings.—The D'Arcy Exploration Company has kindly supplied well cuttings taken, at intervals of 5 to 10 feet, from the circulating mud during the drilling. These cover the depth range of all three evaporite beds. They consist of small rock and mineral fragments, up to $\frac{1}{2}$ inch in length, and have given much information on the less soluble

LOG OF AISLABY BORING IN ESKDALE

POSITION OF BORING – – – – – – – – LONG. 0° 41′ 50″ W. LAT. 54° 27′ 38″ N.

COUNTY – – – – – – – – – – – – – YORKSHIRE – NORTH RIDING

METHOD – – – – – – – – – – – – – ROTARY, 136 FT. DERRICK, POWER – DIESEL

DATE – – – – – – – – – – – – – – COMMENCED – 16·6·38 COMPLETED – 17·11·39

ELEVATION OF ROTARY TABLE – – – – 403 FT. (ABOVE O.D.)

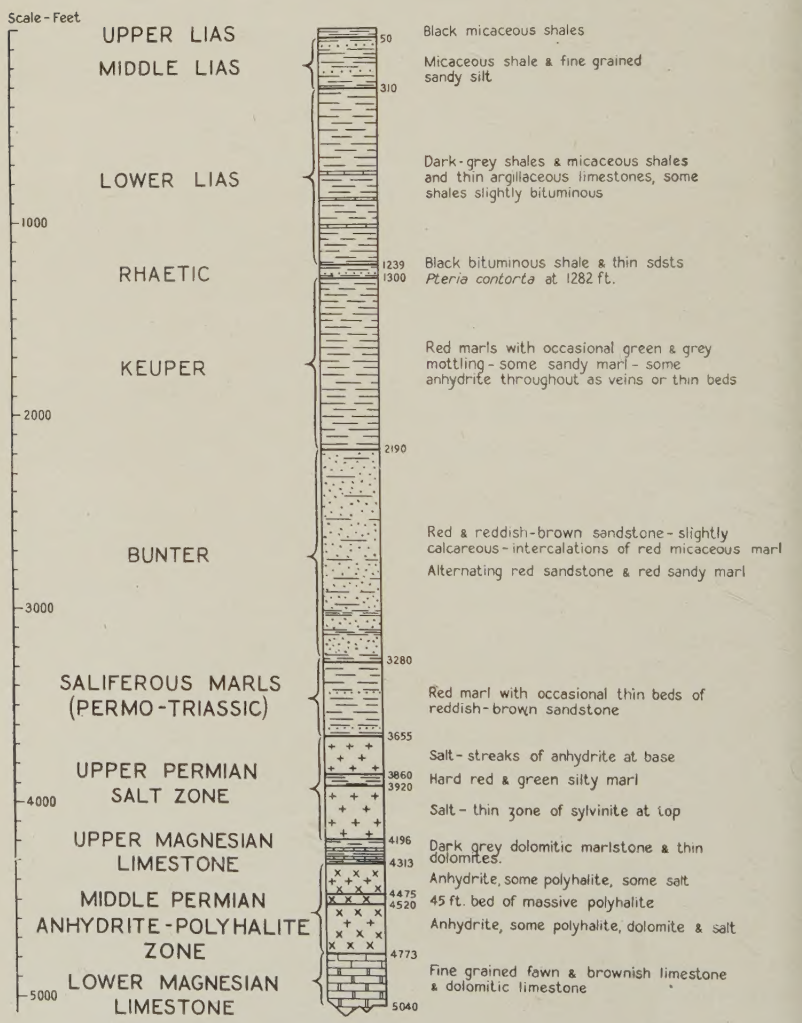


FIG. 1. Log of the Aislaby boring (Eskdale no. 2).
Taken from Lees & Taitt, 1946, (Quart. Journ. Geol. Soc., vol. 101, p. 268.)

minerals. The more soluble minerals are not preserved. From a study of these cuttings the upper limit of a mineral can be fixed with reasonable precision, but the lower limit can be found only approximately.

III. GENERAL SUCCESSION IN THE LOWER EVAPORITE BED.

Since so few core samples of known depth have been preserved, our knowledge of the succession is incomplete. The relative distribution of salt, anhydrite, and polyhalite is given in the following table. The distribution of salt and anhydrite is based on the D'Arcy Exploration Company's detailed log of the boring. It is not known whether other chlorides than halite are present, but it is considered probable that they did not occur in significant amount, if at all, as two specimens from the top 3 feet of the bed show colourless halite with no other chloride. The distribution of polyhalite in the table is based on a study of the well cuttings.

		Thickness in feet.
4313 feet		
Halite-anhydrite zone	Colourless salt	2
	Colourless salt with streaks of anhydrite	10
	Alternating salt and anhydrite	6
	Salt	17
	Alternating salt and anhydrite	7
	Salt with disseminated anhydrite	11
	Alternating salt and anhydrite	16
	Anhydrite with irregular inclusions of salt	7
	Alternating salt and anhydrite	10
4399 feet		
Upper anhydrite	Anhydrite with irregular inclusions of salt	11
	Anhydrite	30
4440 feet		
Polyhalite zone	Salt with irregular inclusions of polyhalite and anhydrite (salt bluish tinge)	34
	Polyhalite with irregular inclusions of salt	30
	Polyhalite	15
	Anhydrite and polyhalite	6
4525 feet		
Lower anhydrite	Anhydrite with occasional irregular inclusions of salt (nests of micaceous mineral)*	12
	Anhydrite	21
	Anhydrite with streaks of salt	5
	Anhydrite with occasional irregular inclusions of salt	15
	Anhydrite (locally dolomitic)	131
	Anhydrite with small irregular inclusions of salt	31
	Brecciated anhydrite with small irregular inclusions of salt	17
	Anhydrite with small irregular inclusions of salt	16
4773 feet		
	Dolomitic limestone ... ... to bottom of boring	

* The micaceous mineral mentioned in the boring log probably refers to talc.

It can be seen that the general sequence of the dominant minerals from the base upwards is carbonate, anhydrite, polyhalite, halite. The sequence, however, is far from ideal. The presence of halite in the lower part of the anhydrite zone is curious. The upper anhydrite zone might indicate freshening of the water at this stage. The upper evaporites of this boring are simpler in this respect, each having a lower sulphate zone, followed by a mixed sulphate-chloride zone and then a thick chloride zone with relatively little associated sulphate.

IV. THE MINERALS.

The following minerals have been found in the lower evaporite bed:

Chlorides: Halite.
Sulphates: Anhydrite, celestine, gypsum, polyhalite.
Carbonates: Dolomite, magnesite.
Other minerals: Pyrite, quartz, native sulphur, talc.

Another mineral occurs in minute quantity in the well cuttings. This has not yet been identified and is under investigation.

Halite, anhydrite, polyhalite, and the carbonates occur in abundance. Talc has been found in many specimens. Gypsum is present only as a product of weathering, but evidence of its former presence on a considerable scale is given by pseudomorphs in the polyhalite zone. Celestine, pyrite, and sulphur occur in very small amount. Quartz forms a few detrital grains.

In the following description the characters and distribution of the individual minerals will be given, with a short summary of their relations to the other minerals. In later sections the mineral assemblages are described and discussed.

(1) *Anhydrite.*

Anhydrite is the most abundant mineral of the evaporite bed. The lower 250 feet is formed almost wholly of this mineral. It occurs in minor quantity in the polyhalite zone. Above this it forms layers and patches in the upper chloride-rich zone and forms a 30-foot bed at the base of this zone.

Most of the anhydrite is white or grey in colour, but some types have a slight bluish tinge. The refractive indices are normal and correspond with those given by Dunham (1948, p. 221) α 1·570, β 1·576, γ 1·614. The grains vary in size from about 0·002 mm. to 1 cm. The shape

varies a great deal. The main types are as follows (there are, of course, gradations from one type to another):

(*a*) Irregular grains with interlocking margins, with a tendency to stumpy rectangular habit.
(*b*) Elongated grains, roughly rectangular with irregular margins. These often tend to form radiate groups.
(*c*) Radiate fan-like plates with curved cleavages, sometimes reaching 1 cm. in length.
(*d*) Rectangular euhedral crystals, generally nearly equidimensional, but sometimes much elongated. These occur associated with halite, and as porphyroblasts in anhydrite-rock.
(*e*) Tabular rectangular euhedral crystals. These occur as porphyroblasts in polyhalite, and sometimes reach nearly 1 cm. in width.

Evidence of recrystallization of anhydrite is widespread, especially where it is associated with halite.

Anhydrite has been found associated with all other minerals of the core specimens. It is generally euhedral towards halite, but has been eaten into and replaced by halite in a specimen from 4559–61 feet (fig. 2). In the polyhalite zone it has replaced gypsum and has been replaced by polyhalite on a large scale. It has partly recrystallized to form large tabular porphyroblasts in polyhalite and these porphyroblasts have themselves been attacked by later polyhalite. Anhydrite has replaced dolomite near the base of the bed, possibly to a considerable extent. Magnesite is nearly always euhedral towards anhydrite, although in a few cases euhedral anhydrite crystals have been seen to cut magnesite plates. Replacement of anhydrite by magnesite has been seen in coarse anhydrite-magnesite-halite-rocks. In the anhydrite-magnesite-dolomite-rock described in a later section, anhydrite appears to be replacing dolomite and it is suggested that brines rich in $MgSO_4$ may cause the production of anhydrite together with magnesite at the expense of dolomite. Plates of talc project from anhydrite into cavities from which halite has probably been dissolved by weathering agents. In one specimen native sulphur has been seen replacing anhydrite. Celestine is euhedral towards anhydrite.

(2) *Celestine.*

This mineral has been found in very small quantity in a specimen of brecciated anhydrite-dolomite-rock from 4742 feet, and in two other specimens of similar rock of unknown depth. It occurs at the edges of

small cavities which probably originally contained halite, and it forms aggregates of elongated crystals up to 1 mm. long, in approximately parallel growth. It is euhedral towards anhydrite. The refractive indices do not differ from those given in the literature, α 1·622, β 1·624, γ 1·631.

Fowler (1944) has recorded celestine, associated with anhydrite, in joints and cavities and as inclusions in dolomite-rock in the Cleveland Hills boring.

(3) *Dolomite.*

The distribution and mutual relations of the carbonates are discussed in a later section. Dolomite is the carbonate present in the lower part of the evaporite bed. It is also the carbonate of the polyhalite-bearing rocks, and is associated with magnesite in the upper anhydrite zone.

In most of these rocks it forms small rounded granules, like those described by Dunham (1948, p. 219), from 0·001 to 0·02 mm. in diameter. These are brown in colour and often crowded with minute dark inclusions. Occasionally they show clear margins or clear centres. They tend to occur in clusters or in strings or thin layers. At the edges of halite cavities they are euhedral, and form small rhombohedra. In some anhydrite-dolomite-rocks the dolomite forms larger clear euhedral rhombohedra up to 0·3 mm. across, in a matrix of anhydrite. Fifteen refractive-index measurements show no significant variation from the value ω 1·682.

Extensive replacement of dolomite by anhydrite is indicated in anhydrite-dolomite-rocks with coarse fibro-radiate anhydrite from the base of the lower anhydrite zone. Dolomite is associated with magnesite in one specimen from the upper anhydrite zone, and the relations suggest that anhydrite and magnesite have formed at the expense of the dolomite. In the polyhalite-anhydrite-rocks, where polyhalite has replaced anhydrite, the carbonate apparently remains unchanged.

(4) *Gypsum.*

Gypsum has been found only as a product of weathering of polyhalite and anhydrite in the well cuttings and in those specimens which were lying in the open for about three years at the site of the boring. Early gypsum was abundant in the polyhalite-bearing rocks.

Very little gypsum has been formed in the weathered anhydrite-carbonate-rocks. In these it occurs principally at the edges of the halite cavities, replacing anhydrite and often enclosing anhydrite relics. Some of the weathered polyhalite-bearing rocks have been entirely converted

to a porous mass of gypsum. Others show a weathered gypsum crust of varying thickness with a central core of fresh polyhalite. The contact of this gypsum crust with the fresh material is remarkably sharp. The gypsum forms a porous mass of elongated crystals up to 5 mm. in length, radiating from the central core (e.g. pl. XXXIII, fig. 37).

Abundant evidence of early gypsum is found in the polyhalite-bearing rocks, where anhydrite, halite, and polyhalite form pseudomorphs after gypsum. The evidence suggests that part of the gypsum was primary, and that some of it was derived from anhydrite in unconsolidated anhydrite-dolomite layers. Later the gypsum was replaced by anhydrite and halite and these were replaced by polyhalite. These rocks are described in detail and discussed in the later sections on polyhalite-bearing rocks.

(5) *Halite.*

This mineral has been preserved only in the core samples of known depth. The bore journal shows that it is the most abundant mineral of the upper 100 feet of the evaporite bed, and the well cuttings show that it is there associated with anhydrite. It is also present in large quantity from 4440 to 4474 feet associated with polyhalite, anhydrite, and talc. It occurs as irregular inclusions in polyhalite-rocks and anhydrite-rocks below this depth at several horizons.

In the core specimens it is colourless, in marked contrast to the predominantly pink or brown varieties of the upper evaporites. The bore journal records a bluish tinge in the halite associated with polyhalite through the depth range 4440–4474 feet.

The grains vary from a few millimetres to about an inch in diameter, and their boundaries are irregular. In general they are nearly equidimensional, but in a specimen from the top of the evaporite bed (4312–14 feet), which consists almost entirely of halite, the grains are markedly flattened, and impart distinct horizontal platy parallelism to the rock, which splits with ease along the cross-section of the core. This is believed to be due to recrystallization under pressure. The available specimens of halite-anhydrite assemblages from the upper part of the evaporite bed show structures indicating that much of the halite of this zone has recrystallized since its formation, as shown by contortion of anhydrite bands.

Halite has been found associated with anhydrite, polyhalite, magnesite, and talc. It is allotriomorphic towards all these minerals. Where halite is in contact with anhydrite, the latter mineral tends to form

larger crystals than it does in the body of the rock. This feature has been commented on by Schaller and Henderson (1932, p. 16) and by Dunham (1948, pp. 222, 223), and it has been suggested that it indicates recrystallization of the anhydrite next to invading halite. It is probable, however, that this texture can arise by recrystallization of anhydrite during recrystallization of halite, without attendant replacement. In the case of the polyhalite-rocks, large crystals of polyhalite are apparently formed at the expense of halite in some cases.

FIG. 2. Halite-anhydrite-rock, showing replacement of anhydrite by halite. 4559–61 feet below surface. ×30.

Direct evidence of the replacement of anhydrite by halite is shown in a specimen from 4559–61 feet. Here the halite encloses small rounded detached relics of anhydrite which have common optical orientation (fig. 2).

Replacement of halite by polyhalite has been seen in the halite-anhydrite-polyhalite-talc-rock from 4445–47 feet and has probably taken place on a considerable scale in the rocks of the polyhalite zone.

Replacement of gypsum by halite is suggested by pseudomorphs in the rock from 4445–47 feet and other rocks of the polyhalite zone. Anhydrite may form an intermediate stage in this replacement (pl. XXX, figs. 21, 22).

No definite replacement relationship has been seen between halite and the carbonates. Talc occurs as thin plates which almost invariably lie along the cleavages of the halite (figs. 19, 20).

(6) *Magnesite.*

This mineral is the carbonate of the halite-anhydrite zone. It occurs with dolomite in the upper anhydrite zone, and also occurs in anhydrite-magnesite-talc-halite-rock which is probably to be referred to a layer near the top of the lower anhydrite zone. The distribution and relationships of magnesite and dolomite are discussed in a later section.

The magnesite forms platy crystals, tabular parallel to (0001), which reach one cm. in width in the coarse anhydrite-magnesite-halite-rocks.

These plates often have ragged edges, but are sometimes edged with a flat rhombohedron. In some rocks they tend to form radiate bunches. In others they occur as isolated crystals, either with even or patchy distribution. Cases have been found where plates have been cut and faulted by later plates.

Twelve refractive index measurements give ω 1·700–1·703, indicating almost pure magnesite. Chemical tests show the virtual absence of calcium and only a trace of iron.

The mineral is always associated with anhydrite, towards which it is almost invariably euhedral. Euhedral crystals sometimes project from anhydrite into halite. It has replaced anhydrite in coarse anhydrite-magnesite-halite-rock (fig. 9 B). In one specimen (4415 feet) euhedral plates of magnesite cut dolomite and the relations suggest that anhydrite and magnesite have formed at the expense of dolomite (fig. 10).

So far as the writer is aware, this boring gives the first record of magnesite in British evaporites.

(7) *Polyhalite.*

This is an important mineral of the lower evaporite bed at Eskdale. The well cuttings show that the polyhalite zone extends from about 4440 to 4525 feet. The cuttings and the detailed log of the boring show that the upper 34 feet of this zone consists largely of chloride, with minor quantities of polyhalite and anhydrite. Below this the rocks consist largely of polyhalite, with subordinate halite and anhydrite, and these grade downwards into massive anhydrite-dolomite-rock. Polyhalite is present in two specimens of known depth (4445-47, 4491–93) and in a large number of specimens of unknown depth.

The mineral normally occurs as fine-grained aggregates (0·001 0·2 mm. grain-size) of irregular grains which may be equidimensional or elongated. The elongated grains may be arranged with random orientation, or in fibrous aggregates or spherulitic groups. Much larger subhedral or euhedral grains (up to 1·5 mm. in length) are occasionally found associated with anhydrite, lining halite cavities, or enclosed in halite (fig. 32). Tiny plates and rods are found in the early stages of replacement of halite and anhydrite.

Most grains of polyhalite show twinning. Lamellar twinning, resembling that of the felspars, is very common. The large euhedral crystals generally show simple or sector twinning. These crystals are generally spear-shaped in section, and may be divided by twinning into two or four parts with different orientation. The crystal-form and twin-

laws have not been worked out, but the crystals are similar to those figured by Schaller and Henderson (1932, p. 53) and described by Görgey (1914).

Measurements of refractive indices give α 1·546, β 1·559, γ 1·568. The average of five measurements of the optic axial angle gives 2V 61°, negative. Chemical analyses of polyhalite-rocks are given in table I (p. 657). The rock *A* consists of almost pure polyhalite.

The origin of the polyhalite-bearing rocks is discussed in detail in a later section, where evidence is given suggesting that the polyhalite has been derived almost entirely by replacement of halite and anhydrite. Gypsum was an early constituent of these rocks, but there is no evidence of direct replacement of gypsum by polyhalite. Polyhalite forms pseudomorphs after gypsum, but it is probable that anhydrite was an intermediate stage in the formation of these. Dolomite has apparently played no part in the replacement. Talc appears to be of later formation than polyhalite.

(8) *Pyrite.*

Pyrite has been found in only one specimen. Two idiomorphic crystal groups have been observed in a slice of an anhydrite-dolomite-rock, embedded in anhydrite and associated with native sulphur. The larger group is 0·5 mm. in diameter.

(9) *Quartz.*

Crystals of quartz occur in fair quantity in parts of the upper evaporites of this boring, but in the lower evaporite only a few small rounded detrital grains have been detected.

(10) *Native Sulphur.*

Sulphur has been observed as small grains in 21 of the well-cutting samples from the upper anhydrite, polyhalite, and lower anhydrite zones. A sample from 4450 feet contains 8 grains of sulphur, and the others 1–3 grains each.

Sulphur has also been seen in two core samples of unknown depth. These consist of anhydrite-dolomite-rock, and the sulphur occurs replacing anhydrite, and also associated with pyrite. The largest aggregate seen is 1·5 mm. across, and encloses corroded anhydrite relics. It is noteworthy that small blebs of sulphur are developed in areas of fine-grained anhydrite which contain a considerable amount of carbonaceous impurity (pl. XXIX, fig. 13).

(11) *Talc.*

Talc has been found to be a widespread constituent of the upper and lower evaporites in the Eskdale boring (figs. 18, 19, 20). As far as the writer is aware, this boring provides the first published record of the occurrence of this mineral in evaporites, and it is very peculiar that it should occur in such a paragenesis.

The mineral occurs in specimens from the halite-anhydrite zone, the polyhalite zone, and the lower anhydrite, and appears to be invariably associated with halite. Its distribution and origin are discussed in a later section.

It occurs as thin plates, up to 5 mm. in diameter, and 0·2 mm. thick. These plates show a pearly lustre on (001), and a perfect micaceous cleavage parallel to (001). They are very soft, flexible, and insoluble in acids. They give a negative pseudo-uniaxial interference figure. The refractive indices are α 1·540, $\beta = \gamma$ 1·588$\pm$0·002. Small liquid inclusions occur along the cleavages.

Dr. F. A. Bannister of the British Museum of Natural History has kindly confirmed the identification by comparing the rotation photograph of a flake of the mineral with that of a talc from Zillerthal. He found that the basal diffractions were identical in position and relative intensities.

Since this mineral was found in the Eskdale evaporites, the writer has heard from W. T. Schaller, in a personal communication, that talc has been found in the Texas–New Mexico salt-field. The mineral described as 'polyhalite fibres (p)' in the legend facing pl. 23 c in Schaller and Henderson (1932) has proved to be talc.

At Eskdale, the plates of talc lie along the cleavages of halite grains. The same is true of the American illustration. It is suggested in a later section that the talc is a late secondary mineral, formed from solutions which were particularly associated with halite.

V. HALITE-ANHYDRITE-ROCKS.

This description is based on those core specimens of known depth which consist largely of halite and anhydrite, without polyhalite. Halite-anhydrite assemblages are preserved in specimens from the following depths: 4312–14, 4314–16, 4350–52, 4352–54, 4356–58, 4559–61 feet.

The first five of these specimens belong to the chloride-rich zone of the upper part of the evaporite bed. They consist of colourless halite

with irregular layers and patches of white or grey anhydrite. Thin sections show the presence of small quantities of magnesite and talc.

The halite forms irregular grains, with interlocking margins, up to about an inch across. In the specimen from 4312–14 feet, the grains (up to 1 cm. across) are flattened, and the rock shows marked horizontal platy parallelism. In the other specimens the grains are nearly equidimensional.

The anhydrite layers and patches are irregular and the thinner layers are contorted and squeezed out in places. In the interiors of the layers most of the anhydrite grains are small (0·001 to 0·2 mm. diameter), and show irregular and interlocking margins. Layers rich in dusty impurities are taken to indicate original bedding, and contortion and crenulation of these has probably been caused by deformation due to recrystallization of the halite enclosing the anhydrite layers, and sometimes partial recrystallization of the anhydrite. Bedding is also indicated by variations in grain-size. In this fine-grained anhydrite, much larger grains are often found (up to 1 mm. in length). These are sometimes euhedral rectangular crystals with sharp boundaries, probably formed by recrystallization. In other cases the larger crystals have corroded edges and appear to be breaking down to form fine-grained material.

Towards the edges of the anhydrite layers, the grain-size generally increases greatly (up to 1 mm.) and well-formed crystals project into halite (fig. 3 B). Small irregular patches of anhydrite in halite sometimes show aggregates of large anhydrite grains surrounding a central core of fine-grained anhydrite. This would indicate either replacement of anhydrite by halite with concomitant recrystallization of anhydrite (Dunham, 1948, p. 223), or breaking up of anhydrite layers by recrystallizing halite (almost a plastic flow effect), with recrystallization of anhydrite.

Where isolated crystals of anhydrite are enclosed in halite, they are euhedral and often fairly large. Sometimes strings of these crystals fringe the halite grains, as if the halite had pushed them out during recrystallization.

A few crystals of magnesite have been found in most of these thin sections. The mineral occurs as platy crystals up to 1 mm. across and 0·2 mm. thick, tabular parallel to (0001). It is euhedral towards halite and anhydrite, and has been seen to cut across the large euhedral anhydrite crystals in fine-grained anhydrite.

A few very thin flakes of talc (up to 0·5 mm. long) lie along the cleavages of the halite in the thin sections of the rock from 4314–16 feet.

The other specimen (4559–61 feet) in which halite has been preserved is from the zone of anhydrite with halite inclusions below the polyhalite zone. It consists largely of anhydrite, with irregular patches of halite. The anhydrite grains are fairly large, and are, in general, of two types—roughly rectangular equidimensional grains and elongated grains with irregular boundaries which often coalesce to form fibro-radiate bunches

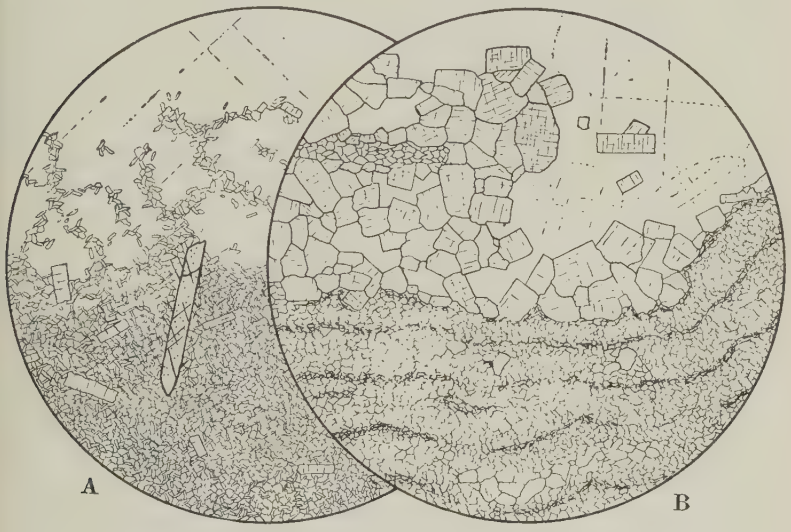


Fig. 3 A. Halite-anhydrite-rock, with magnesite plate. Edge of thinfine-grained anhydrite layer. 4314–16 feet below surface. ×40.

Fig. 3 B. Halite-anhydrite-rock, suggesting recrystallization of anhydrite adjacent to halite. 4350–52 feet below surface. ×17.

and fan-like aggregates. The rectangular grains appear to have formed at the expense of the fan-like type. Many of the grains show cataclastic structures—bending, opening of cleavages, and secondary twinning. The halite occurs in irregular areas and shows direct evidence of replacement of anhydrite by enclosing small rounded anhydrite relics with the same orientation as anhydrite grains adjacent to the halite (fig. 2). A few clusters of minute rounded grains of dolomite have been observed in the anhydrite.

In many of the specimens of unknown depth, consisting largely of anhydrite, cavities indicate the previous presence of halite. All the halite has been removed by weathering.

To summarize the features shown by the anhydrite-halite assemblages:

In the rocks from the upper halite-rich zone we find evidence suggesting considerable recrystallization of the halite since its formation. The rude schistose structure of the halite in the uppermost specimen indicates that in this case recrystallization probably took place after the evaporite had been covered by a considerable amount of rock. The associated anhydrite has at least partly recrystallized. It is possible that the fine-grained centres of the thicker bands are original. No direct evidence of replacement of anhydrite by halite has been found in this zone, although this has possibly taken place. If the large euhedral anhydrite crystals are recrystallized porphyroblasts, then the magnesite crystals cutting these have also recrystallized.

In the rock beneath the polyhalite zone direct evidence of replacement of anhydrite by halite has been observed. There has also been a considerable amount of recrystallization of the anhydrite, which shows no sign of bedding.

VI. ANHYDRITE-CARBONATE-ROCKS.

Practically all available specimens of the rocks consisting largely of anhydrite contain some carbonate. This section therefore includes all the specimens of unknown depth except those containing polyhalite. Three specimens of known depth are included here (4415 ; 4742 ; 4760–62 feet). The well cuttings give some idea of the distribution of the different varieties.

Several of the rocks described here contain irregular cavities which indicate the previous presence of halite. A little residual halite was found in one of these cavities in the middle of a weathered specimen, but such rocks are so porous that in all other cases the mineral has been dissolved out of the samples of unknown depth.

Apart from the halite, anhydrite forms more than 80 % of nearly all these rocks, except the anhydrite-dolomite-rock near the base of the lower anhydrite zone, in which dolomite is sometimes very abundant. Normally, the carbonates are present only in small quantity. Two carbonates have been found—dolomite and magnesite. They have been found together only in one specimen and the relations here suggest that magnesite and anhydrite were being formed at the expense of dolomite. The dolomite in these rocks occurs either as small rounded granules or as larger euhedral rhombohedra. The magnesite forms thin platy crystals, tabular parallel to (0001).

Other minerals found are talc, celestine, sulphur, and pyrite. Talc is present in many of the rocks in halite cavities, forming thin ragged

plates. It occurs in considerable quantity in a few specimens. Celestine, sulphur, and pyrite have been found in very small quantity. A considerable amount of carbonaceous matter is present in certain cases. Gypsum occurs only as a product of weathering, in the specimens of unknown depth.

Bedding structures are not well developed. In some cases they are indicated by thin layers of impurity, often crenulated, or by strings of dolomite granules. Differences in grain-size and texture of different layers may also indicate bedding. Normally the minerals show no sign of platy or linear parallelism.

Evidence of recrystallization of anhydrite is widespread. Cataclastic structures are occasionally found. Evidence of replacement of dolomite by anhydrite on a considerable scale has been found in rocks from near the base of the lower anhydrite zone. As mentioned above, it appears likely that dolomite has been replaced by magnesite and anhydrite in one specimen from the upper anhydrite zone. Magnesite has replaced anhydrite in the coarse anhydrite-magnesite-halite-rock. Sulphur has been seen to replace anhydrite.

On the basis of their petrographic character these rocks can be divided into the following groups:

1. Anhydrite-dolomite-rock (±halite, ±talc).
2. Brecciated anhydrite-dolomite-rock (±halite, ±talc, ±celestine).
3. Anhydrite-dolomite-rock with coarse fibro-radiate anhydrite (±halite).
4. Compact anhydrite-magnesite-rock.
5. Coarse anhydrite-magnesite-halite-rock (±talc).
6. Anhydrite-magnesite-talc-halite-rock.
7. Anhydrite-dolomite-magnesite-rock.

(1) *Anhydrite-dolomite-rock.*

These rocks probably form a large part of the lower anhydrite zone and may also occur in the upper anhydrite. They are fine to medium grained, and light to dark grey in colour. Dolomite is normally present only in small quantity, up to about 5 %. Cavities indicating the previous presence of halite are present in many specimens. Slices show that the anhydrite varies considerably in texture. In some cases it consists largely of a fine-grained interlocking mass of shapeless grains. In other cases the grains tend to express a stumpy rectangular habit. Sometimes they are much elongated. All these types may occur together

in the same specimen. Many of the rocks are almost even-grained, while others show marked variation in grain-size either in a patchy fashion or with a tendency to layering.

The dolomite occurs in two varieties (fig. 4). In many rocks it forms rounded brown granules from 0·001 to 0·02 mm. in diameter, apparently similar to those described by Dunham (1948, p. 219). These occur disseminated through the rock, or in thin layers and clusters giving a

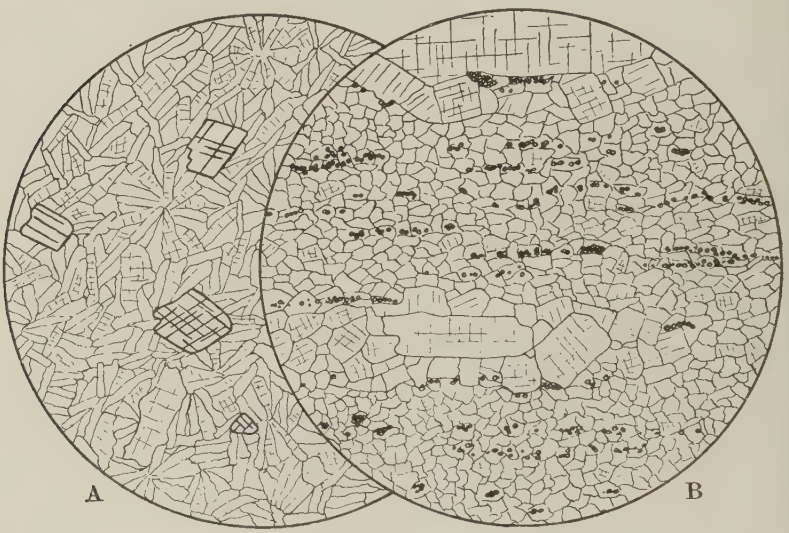


Fig. 4. Anhydrite-dolomite-rocks. ×40.

suggestion of bedding. In other rocks the dolomite forms larger clear euhedral rhombohedra up to 0·3 mm. across, often grouped together in patches. Here the associated anhydrite forms small grains with interlocking boundaries, frequently elongated.

No replacement relationship between dolomite and anhydrite has been seen in these rocks. Replacement of anhydrite by polyhalite in rocks of this general type will be described later.

In one of these rocks pyrite has been found, associated with sulphur. Sulphur has been found in two cases, in small quantity. A few small yellow patches can be seen in the hand-specimen. In one slice two small idiomorphic crystal groups of pyrite are enclosed in anhydrite. Close to these are several aggregates of sulphur up to 1·5 mm. across, and one of the pyrite grains has a small patch of sulphur projecting into it.

The sulphur has been derived, at least in part, from anhydrite, as it encloses relics of this mineral. In one case an elongated anhydrite grain has been cut into four distinct corroded relics. In other parts of the slice, where fine-grained anhydrite is associated with clots of carbonaceous matter, numbers of small rounded patches of sulphur have been developed (pl. XXIX, fig. 13).

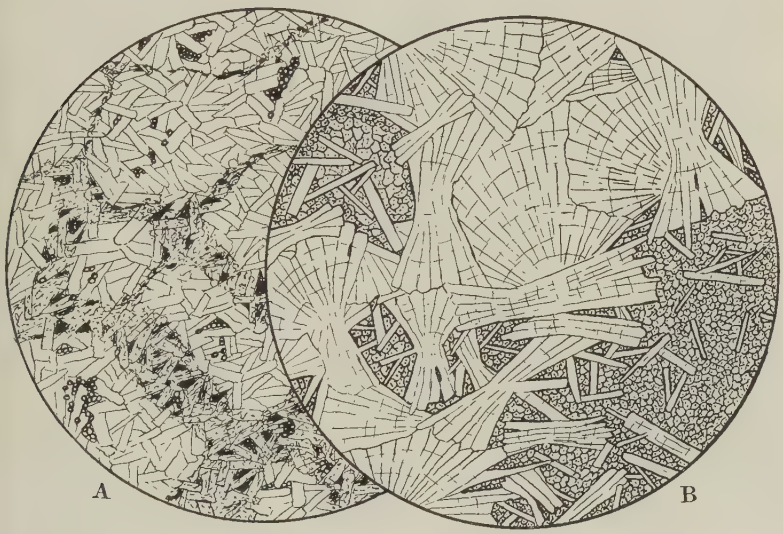


Fig. 5 A. Brecciated anhydrite-dolomite-rock, with carbonaceous impurity. ×20.
Fig. 5 B. Anhydrite-dolomite-rock with coarse fibro-radiate anhydrite. ×10.

(2) *Brecciated anhydrite-dolomite-rock.*

The detailed log of the boring indicates a layer of brecciated anhydrite with small irregular inclusions of salt near the base of the lower anhydrite zone from 4740 to 4757 feet. One specimen of known depth (4742 feet) belongs here, and this and the well cuttings show that the rock is very distinctive, and justify the grouping of several similar specimens of unknown depth in this category.

Hand-specimens show light-coloured fragments up to $\frac{1}{2}$ inch long embedded in a dark matrix. The fragments are sometimes angular and in some cases rounded or flattened and streaky. The matrix is rich in carbonaceous impurity. Small irregular cavities indicate the previous presence of halite, and occasional thin plates of talc are found in these. They are lined with euhedral anhydrite crystals, associated in rare cases

with celestine. They occur mainly in the light fragments, but occasionally in the matrix.

Slices show that the light-coloured fragments consist largely of elongated anhydrite grains, up to 2 mm. long, sometimes arranged in radiate bunches. More or less dolomite is associated with the anhydrite, and this mineral forms small rounded grains which tend to occur in clusters of varying size. The dark matrix is composed largely of anhydrite like that of the fragments, but the grains are crowded with dusty impurities. Some dolomite is also present in this matrix and a considerable amount of carbonaceous material forms interstitial patches between anhydrite laths. The boundaries between fragments and matrix are marked mainly by the distribution of carbonaceous material, and not by the anhydrite, whose grains form a continuous mass cutting across the boundaries. Celestine has been observed in slices of three specimens and in one hand-specimen. It forms small groups of euhedral platy crystals in approximately parallel orientation, about 1 mm. wide, projecting into cavities.

Fig. 6. Brecciated anhydrite-dolomite-rock. Polished surface. Nat. size.

In this rock there is no direct evidence of replacement of dolomite by anhydrite. The structure and textures suggest that a dolomite-anhydrite-rock was broken up on the sea floor and the fragments enclosed by a carbonaceous anhydrite-dolomite mud. Later recrystallization of the anhydrite has to a considerable extent obscured the boundaries between fragments and matrix, but these are now indicated by the distribution of carbonaceous material. The lack of any tendency to parallel orientation of the anhydrite crystals would seem to indicate that recrystallization did not take place under much pressure and was therefore effected early, but later than the flattening and streaking out of the brecciated anhydrite-dolomite fragments (fig. 6).

(3) *Anhydrite-dolomite-rock with coarse fibro-radiate anhydrite.*

The characteristics of this type are that most of the anhydrite occurs as large fibro-radiate aggregates of elongated grains, usually showing a replacement relationship to the dolomite, which forms small rounded grains.

One specimen of known depth (4760–62 feet) belongs to this group, as do several specimens of unknown depth. The well cuttings show that these rocks occur at the base of the evaporite bed, below the brecciated type.

The amount of dolomite present varies considerably. One specimen shows about 40 % dolomite, others much less. In hand-specimens the anhydrite has a bluish tinge, and tends to form fan-like platy aggregates sometimes up to as much as 1 cm. in length. Where dolomite is abundant the rock is brown in colour. In some specimens small irregular cavities are lined with euhedral anhydrite crystals.

Slices show that most of the anhydrite forms much-elongated lath-like grains very often arranged in radiate or fan-shaped bunches. These generally have irregular margins, but are euhedral when cutting dolomite. Dolomite forms small rounded grains, about 0·02 mm. in diameter. These are brownish in colour and turbid with tiny dark inclusions. They occur as patchy aggregates, occasionally showing a central area of larger clear dolomite grains, up to 0·2 mm. across. These aggregates show all stages of replacement by anhydrite. Some are cut through sharply at their edges by elongated euhedral anhydrite crystals. In other cases the anhydrite porphyroblasts develop inside the dolomite areas. In the later stages the anhydrite grains break up the dolomite aggregates so that angular dolomite relics occur interstitially in a mesh of anhydrite crystals. Anhydrite grains have been observed to enclose several relics of dolomite with common optical orientation. In one section a dolomite area has been broken into several pieces by thin veins of fine-grained anhydrite, the anhydrite crystals showing an orientation normal to the walls of the veins. In another case dolomite, partly replaced by elongated anhydrite crystals, is cut by fairly sharp-edged vein-like masses of coarse fibro-radiate anhydrite up to about 1 cm. across. The anhydrite crystals radiate from centres at the edges of the veins (figs. 7, 14).

The well cuttings show that these rocks can almost certainly be referred to the layer below the brecciated anhydrite at the base of the lower anhydrite zone (4757–73 feet). All the rocks with predominantly coarse fibro-radiate anhydrite show replacement of dolomite by anhy-

drite, and this strongly suggests that this basal layer has been formed largely by metasomatic replacement of dolomite due to sulphate-rich brines. This cannot be definitely asserted, since no core series was preserved, but it seems likely.

Fowler (1944) and Dunham (1948) have given impressive evidence of replacement of dolomite by anhydrite in other borings in the Permian evaporites of north-eastern England, and Hollingworth (1948) has recorded such replacement in west Cumberland.

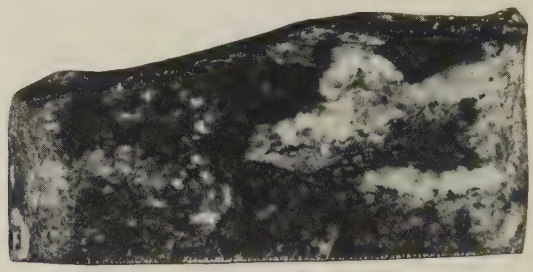


Fig. 7. Vein like masses of anhydrite in anhydrite-dolomite-rock with coarse fibro-radiate anhydrite. Polished surface. ×3/2.

(4) *Compact anhydrite-magnesite-rock.*

Many of the specimens of unknown depth belong to this group. The commonest type is a light grey sugary rock sometimes showing crenulated lines of impurity which appear to indicate original bedding (fig. 15), but usually without any definite bedding structure (fig. 16). Other types are darker and richer in carbonaceous matter. Thin sections show anhydrite, magnesite, and a small amount of very fine-grained impurity. The anhydrite generally makes up 80 to 95 % of the rock, and varies considerably in grain-size and texture. Some slices show an aggregate of stumpy subhedral grains up to 1 mm. in length. Others show a groundmass of irregular interlocking grains about 0·1 mm. in length with larger irregular grains up to 1 mm. scattered through it. In other cases the grains tend to be elongated and occasionally form radiate aggregates. The magnesite is in all cases euhedral, and forms platy crystals, up to 2 mm. in width and 0·3 mm. in thickness, tabular parallel to (0001). Sometimes these plates form radiate sheaves. Many of the crystals contain small shapeless inclusions of anhydrite, and these are sometimes concentrated towards the centre of the crystal. The magnesite forms up to 15 % of the rock. The crystals show no tendency to parallel orientation.

(5) *Coarse anhydrite-magnesite-halite-rock.*

These rocks are very striking in hand-specimens. They are light grey in colour and show large plates of magnesite, up to 1 cm. across, with random orientation, enclosed in sugary anhydrite. The rock is full of small irregular cavities which almost certainly contained halite. The magnesite plates project into and often cut across the cavities. Occasional thin plates of talc also occur in the cavities.

Thin sections show anhydrite, magnesite, and secondary gypsum (figs. 9 B, 17). The gypsum is apparently due to weathering while the specimens were lying in the open at the site of the boring, and tends to occur at the edges of the cavities, replacing anhydrite. Much of the anhydrite forms irregular grains and large fan-like crystals with curved cleavages, up to 5 mm. across. These commonly show strain shadows and bending of grains. They are cut into and sometimes enclose sharp rectangular euhedral crystals of anhydrite, which have apparently recrystallized at their expense. Magnesite forms up to 20 % of the rock and occurs as large thin plates, with cigar-shaped cross-section. It is euhedral towards the anhydrite, and in a few cases shows definite evidence of replacement origin, containing corroded relics of anhydrite with the same optical orientation as the adjacent anhydrite grains (fig. 9 B).

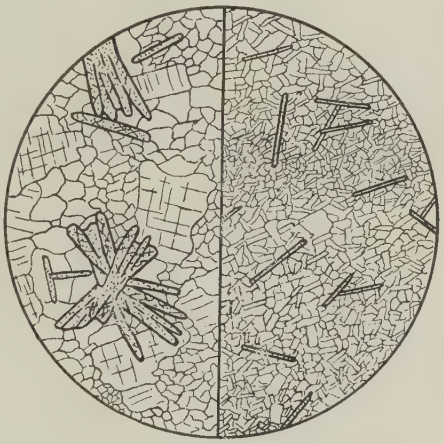


FIG. 8. Anhydrite-magnesite-rocks. ×17.

The relations suggest extensive recrystallization in this rock since its consolidation. Cataclastic structures are common in the fan-shaped and large irregular grains of anhydrite. These are cut by euhedral anhydrite and by magnesite, and as neither of the latter show strain-shadows or bending, they must be of later formation.

(6) *Anhydrite-magnesite-halite-talc-rock.*

In a few specimens talc is fairly abundant in certain bands, as groups of silvery flakes up to 5 mm. across, in small cavities which apparently

contained halite. The rocks are grey or bluish in colour and fine-grained. Slices show anhydrite, magnesite, talc, and a small amount of carbonaceous impurity (figs. 9 A, 18). The anhydrite, which forms about 85 % of the rock, occurs mainly as irregular interlocking grains, sometimes markedly elongated, from 0·05 to 0·2 mm. in size. There are coarser patches where the grain-size reaches 0·5 mm. Through this anhydrite

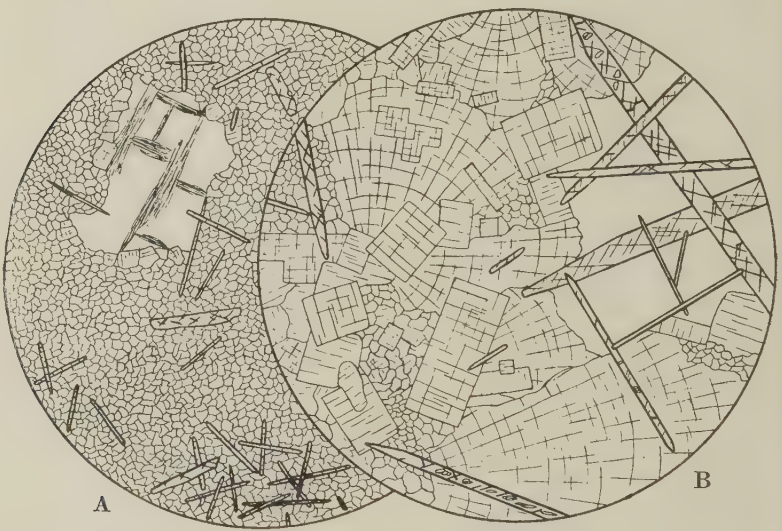


Fig. 9 A. Anhydrite-magnesite-halite-talc-rock, showing a halite cavity crossed by a rectangular network of talc plates. × 10.

Fig. 9 B. Coarse anhydrite-magnesite-halite-rock: Secondary rectangular anhydrite porphyroblasts cut fine-grained and fibro-radiate anhydrite. Some magnesite plates enclose relics of anhydrite with the same optical orientation as the surrounding grains, showing that magnesite has replaced anhydrite. To the right is a halite cavity crossed by a network of magnesite plates. × 10.

are scattered numerous euhedral plates of magnesite, with random orientation, most of these being about 1 mm. wide and 0·05 mm. thick. As a rule they are distributed fairly evenly through the rock, making up about 10 % of it, but there are occasional small patches much richer in magnesite (up to 20 %). In certain layers in this rock, small cavities are seen. The anhydrite lining these cavities often forms relatively large euhedral crystals like those seen in contact with halite in the halite-anhydrite assemblages. These cavities almost certainly contained halite. It is in these that the talc occurs, as thin ragged plates, several millimetres in width. The plates sometimes penetrate the cleavages, some-

times the intergranular boundaries of the anhydrite, at the edges of the cavities. In a few cases they have been seen to cut obliquely across an anhydrite grain. From the anhydrite they cut across the cavities to form a rectangular criss-cross network (fig. 9 B). It is practically certain that this pattern means that talc lay along the cleavages of the halite in the cavities. Wherever talc has been found associated with halite in this evaporite, it lies along the cleavages of the halite.

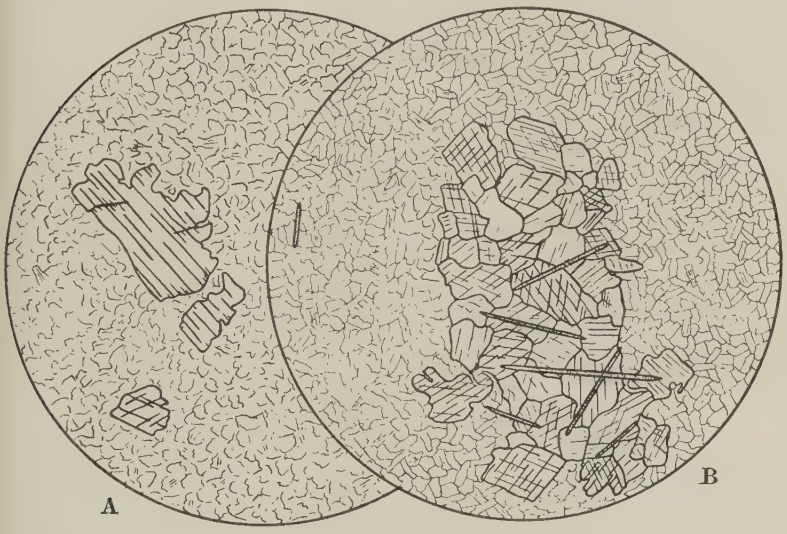


FIG. 10. Anhydrite-dolomite-magnesite-rock. 4415 feet below surface. × 20.
A. Large crystal of dolomite cut in two by replacing anhydrite.
B. Aggregate of dolomite eaten into by anhydrite, while magnesite cuts both dolomite and anhydrite.

The bore journal records a band about 12 feet thick of 'anhydrite with occasional irregular inclusions of salt (nests of micaceous mineral)' from 4525 to 4537 feet below the polyhalite zone. This may refer to the rocks described here.

(7) *Anhydrite-dolomite-magnesite-rock.*

This group is represented by a single specimen from 4415 feet, in the upper anhydrite zone. The rock is especially interesting in being the only one with both carbonates present. It is a dark grey fine-grained rock, with a suggestion of bedding shown by slight differences in colour in different layers. The polished surface shows a few small patches, up

to 5 mm. across, of light brown colour, and slices show that these are dolomite-magnesite aggregates.

The rock is rather like the anhydrite-dolomite-rocks with euhedral dolomite. The anhydrite forms an interlocking mass of small grains, some elongated, 0·002 to 0·2 mm. in length. In this matrix are dolomite grains up to 0·3 mm. across, which tend to occur in groups, and sometimes form relatively large aggregates. Some of these dolomite grains show fairly definite rhombohedral boundaries, but many appear corroded and eaten into by fine-grained anhydrite. The grains are sometimes broken into separate pieces by the invading anhydrite. Magnesite occurs as thin plates up to 1 mm. wide, as dispersed crystals in the anhydrite, and also in the dolomite aggregates. Some of these aggregates, consisting of a large number of dolomite grains, show fine-grained anhydrite apparently eating its way along intergranular boundaries, while euhedral magnesite plates cut through both dolomite and anhydrite (fig. 10 B). The relations suggest that both anhydrite and magnesite may have formed at the expense of dolomite. This is discussed in a later section, where it is suggested that brines rich in $MgSO_4$ might produce magnesite and anhydrite at the expense of dolomite.

VII. POLYHALITE-BEARING ROCKS.

The well cuttings show that the polyhalite zone extends from about 4440 to 4525 feet. By consideration of the detailed log of the boring and the well cuttings, the rocks of this zone can be divided into the following groups:

	Feet
Salt with irregular inclusions of polyhalite and anhydrite	34
Polyhalite with irregular inclusions of salt	30
Polyhalite	15
Anhydrite and polyhalite...	6

The lower layer contains a considerable amount of anhydrite and apparently grades into anhydrite-dolomite-rock at its base. The well cuttings show that small quantities of anhydrite are present in the layers above this.

Only a single specimen (4445–47 feet) is available from the upper halite-rich layer. This is a halite-anhydrite-polyhalite-talc-rock with pseudomorphs after gypsum. The lower layers are represented by one specimen of known depth (4491–93 feet) and many specimens of unknown depth, collected at the site of the boring in 1942. The specimens of unknown depth, containing polyhalite or its alteration product

gypsum, total about 14 feet in length. They had been lying at the site of the borehole, partly embedded in mud, for about three years, and as a result the polyhalite has been partly converted to gypsum by the leaching out of potassium and magnesium sulphates. This alteration has proceeded to various stages in different specimens. The amount of alteration was partly dependent on the amount of anhydrite present in the specimen; some of the anhydrite-polyhalite-rocks show very little change. The alteration was probably also dependent on the protection afforded by the cover of mud, and on the porosity of the gypsum crust. Few of these rocks contain halite cavities and presumably most of the halite-polyhalite-rocks disintegrated rapidly. A total length of about 7 feet of core consists almost entirely of gypsum, but the gypsum derived from polyhalite shows a characteristic structure, and there can be no doubt whatever that these specimens originally consisted almost entirely of polyhalite. The remaining 7 feet or so of core consists of polyhalite and polyhalite-anhydrite-rock, with a gypsum crust of variable thickness.

The polyhalite of the well cuttings has been largely altered to gypsum by the drilling water, although some of the larger cuttings contain some unaltered material. They are therefore of little value for petrological studies, but have given valuable evidence on the depth range of the polyhalite.

The polyhalite of these rocks is white or grey in colour and variable in grain-size and shape. Many rocks show an equigranular texture, the grains being interlocking and anhedral, and the grain-size varying from 0·001 to 0·1 mm. In other cases we find an interlocking mass of small elongated grains. Often the polyhalite forms fibrous aggregates of elongated grains up to 0·2 mm. in length, and these may form radiate groups or spherulitic growths. Tiny plates and rod-like crystals are found in the early stages of replacement of halite or large anhydrite grains. Large euhedral twinned crystals, often spear-shaped, up to 1·5 mm. in length are found enclosed in or projecting into halite, or associated with anhydrite. Often these large crystals appear to have developed by recrystallization of fine-grained polyhalite. In other cases they seem to be breaking down to form finer-grained material. Most of the polyhalite grains show simple, lamellar, or sector twinning.

The other minerals of these rocks are anhydrite, dolomite, halite, and talc. Anhydrite is present in large quantity in some specimens and in small quantity in most. Dolomite is commonly present in small amount, as small granules like those of the anhydrite-dolomite-rocks. Halite has

been preserved in one specimen and small halite cavities occur in several. Talc is especially associated with halite.

Nearly all these specimens give direct evidence that the polyhalite is secondary in origin, and has been derived at the expense of some pre-existing mineral—anhydrite or halite. Many of them give evidence of the previous occurrence of gypsum. In the following petrographic description particular stress will be laid on these replacement effects. Firstly, the rock from the upper halite-rich layer will be described, as it gives evidence of replacement of anhydrite and halite by polyhalite, and of the previous presence of gypsum. Next the development of polyhalite in compact anhydrite-dolomite-rock will be described. This will be followed by consideration of the rocks with abundant polyhalite, which give much evidence of the previous presence of gypsum, and of replacement of anhydrite and halite by polyhalite.

(1) *Halite-anhydrite-polyhalite-talc-rock.*

One specimen (4445–47 feet) shows the association of anhydrite and polyhalite with abundant halite, and this rock gives interesting evidence of the relation of these minerals to one another and of the original occurrence of primary gypsum.

The hand-specimen (pl. XXXIII, fig. 33) shows a marked banding, with layers of colourless halite, as crystals up to one inch across, alternating with complex halite-sulphate layers. The individual layers are up to about an inch in thickness. Talc flakes, up to 5 mm. in diameter and 0·2 mm. thick, are associated with the halite at the edges of the complex layers. The sulphates form a white fine-grained lacy network enclosing irregular areas of halite.

On polished surfaces the complex layers show a fine-scale pseudomorphous structure. Small light-coloured needle-like pseudomorphous crystals, up to 2 mm. long, project into halite from the sulphate-rich layers, and inside these layers are similar pseudomorphs, often consisting of a white rim of sulphate and a dark interior of halite.

Slices (figs. 20, 21, 22) show that the minerals halite, anhydrite, polyhalite, and talc are present. No carbonate has been detected. The halite-rich layers consist almost entirely of halite, with a few flakes of talc and small crystals of anhydrite and polyhalite appearing as the complex layers are approached. In the complex layers the halite forms irregular areas surrounded by a network of anhydrite and polyhalite. Fairly large euhedral crystals of anhydrite and polyhalite (up to 0·5 mm. in length) sometimes project into or are enclosed in halite. Tiny negative

cubic cavities are present in some of the halite grains, and are filled with liquid. In one of these cavities a small bubble has been observed, and this moves if the slice is tilted. Fine-grained anhydrite (grain-size 0·002–0·05 mm.) appears to have once formed the whole of the sulphate network, but it has been partly converted to polyhalite.

The greater part of these complex layers shows the pseudomorphous structure mentioned above. Sometimes the pseudomorphs consist almost wholly of fine-grained anhydrite, but usually they show a central irregular zone of halite with an outer zone of anhydrite. The relative quantities of halite and anhydrite vary considerably. Sometimes the outer anhydrite zone is very thin and in part broken through by the inner halite (fig. 22). The junctions between the two zones are irregular. The outer boundaries of the pseudomorphs are relatively sharp. In cross-sections, the pseudomorphs are roughly hexagonal in outline. In longitudinal sections they are much elongated. The terminations are generally irregular, but are occasionally sharp and shaped like swallow-tail twins of gypsum (fig. 21). Sometimes the original mineral has grown as radiating groups of prismatic crystals. It is believed that these pseudomorphs represent gypsum, although none of the original mineral remains. The interfacial angles in cross-sections of the sharper pseudomorphs agree closely with those of the prism zone of gypsum. Such pseudomorphs are widespread in the other polyhalite-bearing rocks of this boring, and in some cases are remarkably sharp, so that the writer is confident that gypsum was the original mineral. Gypsum pseudomorphs are also widespread in similar rocks of the Texas-New Mexico evaporites (Schaller and Henderson, 1932).

Polyhalite is seen to have partially replaced both anhydrite and halite. Much of the fine-grained anhydrite shows partial or complete replacement by fine-grained polyhalite, the polyhalite often containing darker irregular relics of anhydrite. Sometimes rounded areas of anhydrite in halite have radiate bunches of large euhedral polyhalite crystals growing out from them into the surrounding halite. Large crystals of polyhalite also project from the edges of fine-grained polyhalite areas. In many cases the anhydrite of the outer rims of gypsum pseudomorphs has been converted into polyhalite. Spear-shaped polyhalite crystals are found enclosed in halite inside and outside these pseudomorphs.

Where irregular halite areas are enclosed in a polyhalite network, the polyhalite can be seen to be encroaching upon the halite (fig. 20). This replacement begins with the development of clouds of minute rod-like or rounded platy crystals of polyhalite, scattered with random orienta-

tion through the halite near the edges of the halite areas. These tiny crystals grow larger and more numerous until all the halite has been replaced by a uniform interlocking mass of polyhalite grains. Occasionally the polyhalite develops as small spherulitic growths in halite.

The talc in this rock forms thin plates lying along the cleavages of the halite (fig. 20). It is fairly abundant. The plates often form a rectangular network along the halite cleavages. They show no sign of having developed at the expense of any other mineral, but occasionally several plates seem to have formed from some sort of central nucleus. Their edges occasionally cut into polyhalite or anhydrite crystals. They have not been found in the fine-grained polyhalite derived by replacement of halite, and are therefore probably of later formation than the polyhalite.

It seems likely that this rock originally consisted of halite interbanded with gypsum-halite layers. There is no evidence that the gypsum was not original. This gypsum has been replaced by anhydrite and halite. Were these minerals formed simultaneously, or did one precede the other? The change from gypsum to halite would require removal of gypsum and deposition of halite, as there is no common chemical constituent involved. Such infiltration pseudomorphs have been described by Schaller and Henderson (1932, p. 34), and are found in the upper evaporites of the Eskdale boring. The change from gypsum to anhydrite is a simple one, requiring removal of water. In the latter change there would be a volume contraction. It is interesting in this connexion that the halite occurs in the interiors of the pseudomorphs. If increased concentration of the brines converted gypsum to anhydrite, the resulting shrinkage might leave spaces in the centres of the pseudomorphs, in which halite could be deposited. The wide variation in the relative amounts of halite and anhydrite in these pseudomorphs, and the fact that some of them have only a very thin outer zone of anhydrite, would suggest that part of the anhydrite or gypsum has been removed and replaced by halite. This may have taken place almost simultaneously with, or at a later date than, the initial change of gypsum to anhydrite.

It appears likely, then, that the first replacement effects in this rock were:

Gypsum → anhydrite → halite.

We have evidence of replacements by polyhalite at a later date:

Anhydrite → polyhalite.
Halite → polyhalite.

The latter changes were effected by brines rich in potassium and magnesium. These brines must have been capable of removing some $CaSO_4$, as there is no sign of volume change in the first replacement, and they must also have removed NaCl.

Apparently, at a still later date, talc plates formed in the cleavages of the halite.

It is unlikely that the halite of this rock has suffered appreciable recrystallization since Permian times, as the pseudomorphs are apparently undisturbed.

(2) *Development of polyhalite in compact anhydrite-dolomite-rock.*

The early stages of the development of polyhalite at the expense of anhydrite are well shown by a specimen of unknown depth which consists largely of anhydrite, with scarce, small rounded grains of dolomite. The hand-specimen looks like a typical anhydrite-dolomite-rock, consisting of fine-grained anhydrite with larger subhedral grains. Slices show that most of the rock consists of small irregular grains of anhydrite. Much larger subhedral crystals or groups of crystals are distributed through this matrix. Small dolomite granules are present as clusters and strings in the fine-grained material. In fact, apart from the presence of polyhalite, this rock is typical of the compact anhydrite-dolomite-rocks described in an earlier section.

Polyhalite is found attacking both the fine-grained material and the larger subhedral grains. The larger grains are replaced by fine fibrous masses of polyhalite along their boundaries and along cleavages and cracks (fig. 23). Many of these crystals are separated into several parts by tiny veinlets of fibrous polyhalite which connect with irregular areas of fine-grained polyhalite in the groundmass. Rod-like or platy grains of polyhalite appear inside the large anhydrite grains, and sometimes larger spear-shaped crystals occur. The rod-like grains may have a random distribution or may tend to form radiate groups. In the groundmass of the rock, fine-grained polyhalite forms irregular areas. Under high magnification, the polyhalite can be seen to be eating into fine-grained anhydrite in the same way as it replaces the larger crystals. The strings and clusters of dolomite granules are found in both polyhalite and anhydrite, and appear to have played no part in the replacement.

Here we have an early stage in the replacement of anhydrite by polyhalite in anhydrite-dolomite-rock. If this process were continued, the final product would be a polyhalite-dolomite-rock, showing little trace of its replacement origin, except in the presence of strings and

clusters of the original dolomite (fig. 24). Several specimens of such rocks have been found, though most of these contain a little residual anhydrite in certain layers. In many cases thin bands of this type are found, alternating with bands of polyhalite-anhydrite-rock or polyhalite-rock, containing pseudomorphs after gypsum. There is reason to believe that in some cases secondary gypsum grew in anhydrite-dolomite-rock, and was later replaced by anhydrite and polyhalite. This will be discussed below.

(3) *Polyhalite-bearing rocks with pseudomorphous structure after gypsum.*

The majority of the specimens of polyhalite-bearing rock show a definite pseudomorphous structure, indicated by differences in colour from light to dark grey. The pseudomorphs are believed to represent previous gypsum crystals which have been completely replaced by anhydrite and polyhalite. The original mineral formed elongated prismatic crystals. The edges in the prism zone are often sharply indicated by lines of impurity, or by sudden changes in texture of the polyhalite, inside and outside the pseudomorphs. Cross-sections are hexagonal in outline, and measurements, in thin sections, of the interfacial angles in the prism zone correspond closely with those of the (110) and (010) forms of gypsum. The terminations of the pseudomorphs are generally irregular, but agree in general inclination with the common pyramids of gypsum. In several cases the terminations show twinning of 'swallow-tail' type (fig. 39).

The longest pseudomorph observed is about $1\frac{1}{2}$ inches in length and $\frac{1}{4}$ inch in width, but most are considerably smaller than this. They show a marked tendency to grow in a vertical direction in the core, often in groups radiating from centres at the edges of layers of more uniform material below. Analogy with the vertical growths described by Schaller and Henderson (1932) indicates that they grew upwards rather than downwards, although we do not know which were the upper sides of the Eskdale specimens.

Many of the larger specimens show a layered structure in which layers composed largely of pseudomorphs alternate with more massive layers without much trace of pseudomorphous structure (pl. XXXIV, fig. 38). The massive layers often show thin approximately horizontal bands of dark impurity (fig. 37), perhaps indicating original bedding, and are believed to have originally been anhydrite-dolomite layers. At the upper edges of these massive layers, pseudomorphs appear and grow

upwards to form layers composed largely of pseudomorphs. At the top of the pseudomorphous layers, the pseudomorphs project into the next layer of massive material. In a few cases pseudomorphs have been observed to break through from one pseudomorphous layer to the next. In these cases the lines of impurity of the massive layers can sometimes be traced passing through the pseudomorphs, but partly distorted by them, as though the gypsum crystals had grown partly at the expense of anhydrite in an unconsolidated anhydrite-dolomite mud.

The pseudomorphous structure is shown particularly well by rocks containing a considerable amount of anhydrite as well as polyhalite. In most of such rocks the anhydrite is largely confined to the pseudomorphs, and is scarce or absent in the interstices. Sometimes the pseudomorphs consist almost entirely of anhydrite, of medium grain-size. In this anhydrite are a few relatively large (up to 0·5 mm.) twinned subhedral polyhalite grains. Fine-grained polyhalite can be seen eating its way into the anhydrite at the edges of the pseudomorphs (pl. XXXI, fig. 25). Adjacent pseudomorphs show further stages in this type of replacement, the fine-grained polyhalite encroaching farther on the anhydrite, sometimes in an irregular way, so that the anhydrite area gets broken up and grows smaller and smaller until it finally disappears. The larger subhedral polyhalite crystals break down to form finer-grained material and eventually the pseudomorph consists entirely of fine-grained polyhalite, separated from that of the interstices by a thin brownish line of impurity (fig. 28). Ultimately this line of impurity may also disappear, so that the final product is a uniform rock composed of fine-grained polyhalite. Usually slight differences in texture between the polyhalite derived from the pseudomorphs, which tends to be equigranular, and that of the interstices, which is usually fibrous, indicate the replacement origin of the rock.

In many cases the pseudomorphs of anhydrite are attacked by polyhalite at their centres as well as at the edges. This produces a simple zoned structure which is often obvious in hand-specimens. The intermediate anhydrite zone is darker in colour than the outer and inner polyhalite zones. The zones are irregular and the anhydrite zone is frequently broken across by irregular masses of polyhalite.

In a few specimens a much sharper and more regular multiple zoning is seen (figs. 11, 27, 35). Again the zones are composed alternately of anhydrite and polyhalite, and are parallel to the edges of the pseudomorphs. As many as six zones have been observed in the pseudomorphs of one specimen. Here the centre of each anhydrite zone is marked by

a sharp, thin brown band, rich in dusty impurity. The anhydrite zones are relatively thin and are being encroached upon by the polyhalite zones. In this rock the outermost zone consists of anhydrite and the innermost zone of polyhalite. The anhydrite of the outer zone sometimes continues into the interstices of this rock.

Occasionally, longitudinal sections of pseudomorphs show a curious 'herring-bone' structure, quite distinct from the zoning described above (figs. 12, 39). This is emphasized in specimens which have been polished

Fig. 11.

Fig. 12.

Fig. 11. Zoning in pseudomorphs of anhydrite and polyhalite after gypsum. The upper two diagrams show simple zoning, the edges of the pseudomorphs being marked by lines of impurity. The anhydrite is stippled. $\times 3\frac{1}{4}$.

Fig. 12. 'Herring-bone' structure in anhydrite-polyhalite pseudomorphs after gypsum. The anhydrite is stippled. $\times$ 2.

and then submerged in water for a few minutes. When dried, the polyhalite is covered with a thin white crust of gypsum, while the anhydrite remains dark grey. The structure is seen in 'swallow-tail' twin pseudomorphs. These have an outer zone of anhydrite, and a central partition of anhydrite, or sometimes of polyhalite, along the composition-plane of the twin. On either side of this partition, bands of anhydrite alternate with polyhalite areas to form a 'herring-bone' structure roughly parallel to the terminal faces. Similar structures involving anhydrite and halite are found in the upper evaporites.

In most of the polyhalite-anhydrite-rocks consisting largely of gypsum pseudomorphs, the interstices between the pseudomorphs consist almost entirely of fine-grained fibrous polyhalite, in which the fibres are perpendicular to the edges of the pseudomorphs (figs. 25, 26, 28). In most cases anhydrite and dolomite are completely absent from the interstices, even when the pseudomorphs consist largely of anhydrite. In these cases it is believed that halite originally occupied the interstices. In

a few specimens the interstices bear central cavities, lined with euhedral polyhalite crystals. A few small plates of talc have been observed in such cavities in two specimens, indicating the previous presence of halite.

A few specimens, including one with sharp multiple zoning in the pseudomorphs, show residual anhydrite and dolomite in the interstices. These may represent original anhydrite-dolomite-rock, in which gypsum developed at the expense of anhydrite.

Dolomite is scarce in these rocks. Where present it forms small rounded granules exactly like those of the compact anhydrite-dolomite-rocks. In one specimen, however, it is abundant, forming about 10 % of the specimen. This is a most curious rock. It consists entirely of polyhalite and dolomite. It is banded, one band showing many small polyhalite pseudomorphs after gypsum, each with an outer zone of dolomite granules (fig. 29). Other parts of the rock show an irregular mottling due to the aggregation of dolomite granules in strings and clusters enclosing irregular areas of polyhalite. The meaning of this structure is not clear. It is possible that gypsum crystals grew in anhydrite-dolomite mud unusually rich in dolomite, and that the polyhalite which later replaced the anhydrite of the interstices managed to push the dolomite grains to the edges of the pseudomorphs. The mottled structure of the rest of the rock might be caused by polyhalite crystallizing from various centres in the anhydrite, the polyhalite of one centre pushing the dolomite forward until it met another growth of polyhalite.

(4) *Rocks consisting almost entirely of polyhalite.*

Many of the specimens of unknown depth consist entirely or almost entirely of polyhalite, with subordinate dolomite, and with little or no trace of residual anhydrite. Most of these rocks evidently represent a late stage in the replacement of the rocks described in the preceding section (figs. 28, 40, 41). These show pseudomorphs of polyhalite after gypsum, marked by slight differences in colour between pseudomorphs and groundmass. In slice, the structure is shown by lines of impurity or variations in texture. The rocks also tend to develop cracks along the edges of the pseudomorphs. Occasionally, the presence of pseudomorphs cannot be detected in thin sections, but is apparent in polished specimens.

A few specimens of polyhalite-rock show no trace of pseudomorphous structure, but show lines of dolomite granules and dusty impurity, often crenulated, giving an approximately horizontal banding (figs. 24, 37). This would seem to indicate original bedding, and these rocks are

believed to represent original anhydrite-dolomite-rocks. In many cases a few grains of corroded residual anhydrite are found, and in some cases large anhydrite porphyroblasts which show all stages of attack by polyhalite. Rocks of this type are interbanded with the types consisting largely of pseudomorphs after gypsum, and sometimes contain a few such pseudomorphs themselves.

Very few of the polyhalite rocks show no sign of pseudomorphous or bedding structures. These consist of uniform fine-grained polyhalite, with occasional aggregates of coarse, subhedral polyhalite grains radiating into small cavities which are believed to have contained halite (fig. 32). The cavities are abundant in certain layers (fig. 34). Layers of this type are occasionally found in the rocks described above, and probably represent original halite layers, almost completely replaced by polyhalite.

Nearly all the rocks consisting almost entirely of polyhalite show structures indicating a replacement origin. The very few rocks which show no direct evidence of pre-existing minerals apparently occur interbanded with the replacement rocks, indicating that they too were formed by replacement.

(5) *Anhydrite porphyroblasts in polyhalite-bearing rocks.*

Several of these specimens show large platy rectangular porphyroblasts of anhydrite enclosed in polyhalite-rock. The plates are sometimes as much as a centimetre across and a few millimetres in thickness. They are sometimes sharply euhedral, but generally show evidence of corrosion and conversion to polyhalite, the crystals often being broken into many detached pieces. They are found in polyhalite-anhydrite pseudomorphs after gypsum (fig. 30), and in polyhalite-rocks with bedding structures probably derived from anhydrite-dolomite-rocks (figs. 31, 36). Schaller and Henderson (1932, p. 65) have recorded similar crystals in the polyhalite-rocks of Texas and New Mexico, and have suggested that they are due to recrystallization of excess $CaSO_4$ during replacement of anhydrite-rock by polyhalite, the secondary anhydrite crystals being later partly transformed to polyhalite by continuation of the replacement process or by later brines.

(6) *Chemical composition.*

The results of chemical analyses of three polyhalite-bearing rocks are given in table I. The rock *A* consists of fine-grained massive polyhalite with only a trace of carbonate. Patches of fibrous polyhalite suggest

that the rock is pseudomorphous after halite-rock. Halite cavities occur in neighbouring layers. The analysis shows very close agreement with the calculated composition of polyhalite.

The rock *B* is a polyhalite-dolomite-rock, derived from original anhydrite-dolomite-rock. It consists of fine-grained polyhalite with less than 1 % of minute granules of dolomite, and a few corroded grains of residual anhydrite (about 0·5 %). The dolomite granules are arranged in strings and thin layers, giving an indication of original roughly horizontal bedding.

The rock *C* (pl. XXXIV, fig. 40) is a polyhalite-rock, showing well-developed pseudomorphs after gypsum, consisting of nearly equidimensional polyhalite grains, with interstices of fibrous polyhalite after halite. A trace of carbonate is present, and a little secondary gypsum.

TABLE I. Chemical analyses of polyhalite-bearing rocks

	A.	B.	C.	D.
SO_3	53·04	52·50	52·87	53·11
MgO...	6·72	6·87	6·47	6·68
CaO...	18·71	18·90	18·62	18·61
Na_2O	nil	0·02	0·01	—
K_2O...	15·64	15·42	15·53	15·62
$H_2O+110°C.$	5·92	5·77	5·87	5·98
$H_2O-110°C.$	0·16	0·07	0·13	—
CO_2	trace	0·39	trace	—
Cl	nil	nil	nil	—
Insol.	0·18	0·27	0·18	—
	100·37	100·21	99·68	100·00

A. Polyhalite-rock, derived from original halite-rock.

B. Polyhalite-dolomite-rock, derived from original anhydrite-dolomite-rock.

C. Polyhalite-rock, derived from original gypsum-halite-rock.

D. Calculated composition of polyhalite, $Ca_2MgK_2(SO_4)_4.2H_2O$.

VIII. ORIGIN OF THE POLYHALITE-BEARING ROCKS.

The evidence given above shows that practically all the available specimens of polyhalite-bearing rock have had a complex history and do not represent original precipitates. All specimens containing anhydrite or halite as well as polyhalite show evidence of replacement of these minerals by polyhalite. Most of those consisting entirely of polyhalite (with accessory dolomite) show pseudomorphous structures indicating a replacement origin. The very few specimens which show no definite evidence of replacement and consist of uniform fine-grained polyhalite may well represent the ultimate stage in replacement of

halite-rock or anhydrite-rock. There is no evidence of direct precipitation of polyhalite in the Eskdale evaporites. In fact it is considered certain that most, and probable that all the polyhalite of the available specimens is due to metasomatic replacement of anhydrite and halite by the action of later brines rich in potassium and magnesium. This does not preclude the possibility of direct precipitation of polyhalite, since the available specimens represent only part of the core of the polyhalite zone.

Many of these rocks show evidence of the previous occurrence of gypsum, which is now represented by pseudomorphs consisting of anhydrite, halite, or polyhalite. In some cases, where the gypsum pseudomorphs are enclosed in halite or in fine-grained fibrous polyhalite apparently derived from halite, the evidence suggests that the gypsum was a primary mineral. In other cases, where the pseudomorphs are enclosed in polyhalite-dolomite-rock with residual anhydrite, the mineral was apparently derived from anhydrite, as the bedding structures of the groundmass pass through the pseudomorphs.

In considering the original nature of these rocks it is relevant to refer briefly to the succession in the upper Eskdale evaporites. Fortunately a larger number of specimens of known depth have been preserved from these, although the sequence is by no means completely represented. Each of these evaporites possesses a basal zone of massive anhydrite-rock with subordinate carbonate. This is followed upwards by a complex zone consisting largely of anhydrite and halite with subordinate carbonate. Above this is a thick zone consisting largely of chlorides. It is the intermediate complex zone which throws considerable light on the origin of the polyhalite-bearing rocks of the lower evaporite.

The complex zones of the upper evaporites show alternations of anhydrite-carbonate-rock with bedding structures, anhydrite-halite-rock with pseudomorphs after gypsum, and bands of almost pure halite-rock. The anhydrite-carbonate layers are often massive, but occasionally contain pseudomorphs of halite and anhydrite after gypsum, the pseudomorphs sometimes enclosing and sometimes distorting the bedding structures. The anhydrite-halite layers consisting largely of pseudomorphs show anhydrite-halite pseudomorphs after gypsum, with either anhydrite or halite in the interstices. Simple zoning of pseudomorphs is found, the zones consisting of anhydrite and halite. 'Herring-bone' structure is beautifully developed in some cases, and is identical with that of the rocks of the lower evaporite bed except that halite takes the place of the polyhalite of the latter rocks.

It is believed that the rocks of the polyhalite zone of the lower evaporite bed are due to the metasomatism of rocks similar to those of the complex zones of the upper evaporites. However, even these have suffered changes since their original deposition —particularly in the replacement of gypsum by anhydrite and halite. The polyhalite zone of the lower evaporite bed occupies a similar position in the sequence to that of the complex zones of the upper evaporites. It lies above anhydrite-dolomite-rock and has a halite-rich upper part. The upper anhydrite above it may be due to interruption of the normal sequence by freshening of the water.

It is probable that the polyhalite zone originally consisted of a series of layers of halite-, gypsum-halite-, and anhydrite-dolomite-rocks. The presence of early gypsum at this stage in all three evaporite beds is curious. Experimental evidence suggests that gypsum should form early in the evaporation sequence, when the brines were relatively dilute. Posnjak (1938, 1940), studying the system $CaSO_4$–H_2O and the stability relations of gypsum and anhydrite in sea-water at 30° C., has shown that during evaporation below 42° C. (the transition point gypsum–anhydrite) the calcium sulphate should first precipitate as gypsum, at about 3·35 times the normal salinity, and that anhydrite should not appear until the water has reached about 4·8 times the usual salinity and a considerable amount of gypsum has been precipitated. In the Eskdale evaporites the basal sulphate layer consists of anhydrite-carbonate-rock. There is no evidence that this anhydrite has been derived from pre-existing gypsum. Even where halite is present below the polyhalite zone, there is no sign of pseudomorphs after gypsum like those so abundant in the polyhalite zone and the intermediate zones of the upper evaporites. Dunham (1948) has indicated that the anhydrite near the edge of this salt-field is primary. The basal anhydrite zones of all three evaporite beds at Eskdale are followed upwards by zones with abundant pseudomorphs after gypsum. Some of the gypsum here is believed to be primary, and some to have been derived from anhydrite in unconsolidated anhydrite-dolomite layers. At any rate, the gypsum here was formed before the advent of the brines which introduced polyhalite and is therefore presumably early, being replaced by anhydrite and halite before polyhalite appeared. In these evaporites gypsum appears to have been a transitory mineral, stable only for a short period during the early stages of chloride deposition. In the complex zones slight changes in conditions caused alternate deposition of thin anhydrite-dolomite layers and gypsum-halite layers. Rhythmic changes in

temperature might have been responsible for this, but other factors must have been responsible for the development of gypsum at this stage in all three distinct evaporites.

Schaller and Henderson (1932) have described rather similar rocks, with pseudomorphs of halite after gypsum sometimes replaced later by polyhalite. In the Texas-New Mexico rocks there is apparently no evidence of primary gypsum and the pseudomorphs are enclosed in anhydrite-rock. All the same, the gypsum was of earlier formation than polyhalite, and the authors suggest that it may have formed while the rocks were in a mushy state. It is significant that the general sequence is similar to that at Eskdale. The authors give vertical sections from three borings showing clay, overlain by anhydrite, and the latter by anhydrite with pseudomorphs of halite after gypsum (1932, p. 36).

Let us now consider the details of the replacements which have transformed these halite-, gypsum-halite-, and anhydrite-dolomite-rocks into the existing polyhalite-bearing rocks.

Layers of almost pure halite are found in the halite-anhydrite-polyhalite-talc-rock from 4445–47 feet (fig. 33). Here polyhalite is seen to have replaced halite to a slight extent, adjacent to the sulphate-bearing layers in the rock. It is possible that the few uniform polyhalite-rocks of unknown depth may have been formed by replacement of halite-rock, and some of these contain cavities lined with euhedral polyhalite crystals (fig. 34). The detailed log of the boring shows that halite is the predominant mineral of the upper part of the polyhalite zone, but since this is represented by only a single specimen, we know practically nothing of these rocks.

Halite-gypsum layers are represented by the halite-anhydrite-polyhalite-talc layers in the specimen from 4445 47 feet (figs. 21, 22). These layers probably represent practically contemporaneous precipitation of gypsum and halite. The evidence suggests that the gypsum was primary and was later converted to anhydrite and halite. Halite occupies the centres of the pseudomorphs and it is possible that the shrinkage in the conversion of gypsum to anhydrite allowed access to the halite-bearing solutions. Part of the secondary anhydrite was probably attacked by halite, and both halite and anhydrite have been partially replaced by polyhalite. The changes can be represented as follows:

Gypsum → anhydrite → halite → polyhalite.

Gypsum → anhydrite → polyhalite.

Halite → polyhalite (in the halite matrix).

Many of the specimens of unknown depth were probably originally primary gypsum-halite-rocks (e.g. figs. 25, 26, 28, 40, and pseudomorphous layers of figs. 38, 39). These now consist of pseudomorphs of anhydrite, or polyhalite or both, after gypsum, and interstices filled with fibrous polyhalite. The absence of residual anhydrite and dolomite from these interstices, and the occasional presence of interstitial cavities containing talc, suggest that the original mineral here was halite. In these rocks we have further evidence of the replacements mentioned above. The gypsum has been converted to anhydrite, and the simple zoning and 'herring-bone' structure in the pseudomorphs is so like that of the anhydrite-halite pseudomorphs of the upper evaporites that halite also has probably been involved in the replacement. The anhydrite and halite of pseudomorphs and interstices has then been replaced by polyhalite.

The primary *anhydrite-dolomite layers* are now represented by one specimen showing the early stages in the development of polyhalite at the expense of anhydrite (fig. 23), and by other specimens which consist largely or wholly of polyhalite with residual dolomite (figs. 24, 31, 36, 37). The arrangement of thin layers of dolomite and dusty impurity indicates original roughly horizontal bedding. Some residual anhydrite is often present. The replacement here is:

Anhydrite → polyhalite,

the dolomite apparently remaining unchanged.

Some of these layers derived from anhydrite-dolomite-rock contain pseudomorphs after gypsum. The continuation of thin layers of impurity from the matrix through the pseudomorphs indicates that the gypsum here was secondary, and derived from pre-existing anhydrite. The disturbance of these layers of impurity at the edges of the pseudomorphs indicates that the gypsum may have grown before the matrix had properly solidified. The gypsum has later been changed back to anhydrite and this replaced by polyhalite. The sequence is as follows:

Anhydrite → gypsum → anhydrite → polyhalite.

The multiple zoning present in some of these pseudomorphs is extremely like that figured by Dunham (1948, p. 225 and pl. X, fig. 1), in which secondary gypsum in anhydrite-dolomite-rock contains zones of residual anhydrite. This might suggest that polyhalite has directly replaced gypsum in such zoned pseudomorphs, but the polyhalite-bearing rocks give no other evidence of direct replacement of gypsum by polyhalite, and it seems probable that the Eskdale pseudomorphs

consisted of anhydrite and halite zones. Such pseudomorphs could be derived from gypsum-anhydrite pseudomorphs by solution of the gypsum by halite-depositing brines. This seems to have happened in the upper evaporites, and the writer thinks it likely that the rocks of the polyhalite zone were similar to those of the upper evaporites before the appearance of polyhalite.

Hollingworth (1948, p. 197) has suggested that the gypsum porphyroblasts which are widespread in anhydrite-rocks in other parts of this salt-field may have similar origin to those of the Texas-New Mexico salt-field and may be of fairly early formation. The porphyroblasts in the Billingham anhydrite mine are much less regular than the pseudomorphs of the Eskdale rocks, and do not show such a marked tendency to grow upwards. However, it seems likely that, as Hollingworth suggests, they were of relatively early formation and not due to hydration of anhydrite by meteoric waters.

The changes gypsum → anhydrite and anhydrite → gypsum require only subtraction or addition of water. The changes gypsum → halite and anhydrite → halite require solution and removal of these minerals and deposition of halite in their place, as there is no common chemical constituent involved.

The replacement halite → polyhalite requires removal of halite and introduction of polyhalite. That from anhydrite → polyhalite requires addition of K_2SO_4, $MgSO_4$, and H_2O. In the latter change the $CaSO_4$ of the polyhalite was presumably derived from the anhydrite, and a good deal of $CaSO_4$ must have been carried away in solution, since there is no sign of volume change. Some of the excess $CaSO_4$ recrystallized to form porphyroblasts of anhydrite in polyhalite-rock, and these were attacked by later polyhalite. Some of the excess $CaSO_4$ may have taken part in the replacement of halite by polyhalite.

It seems likely that the replacements described in this section took place during the formation of the evaporite. The early formed gypsum presumably became unstable in the presence of brines of changing composition and concentration, percolating from above, and was pseudomorphed by anhydrite and halite, and these minerals were later replaced by polyhalite when the overlying brines became rich in potassium and magnesium. The upper anhydrite may be due to a freshening of the water, stopping this replacement and sealing off the polyhalite zone. If material becomes available from future borings in this region, it will be interesting to find out whether the lower part of the upper anhydrite shows any development of polyhalite. If it does, then the brines

responsible for the metasomatism may have migrated into the rocks of the polyhalite zone at a late stage.

Schaller and Henderson (1932) have shown that most of the polyhalite of the Texas-New Mexico salt-field is secondary, and has been formed by replacement of anhydrite, halite, and gypsum. They have described many of the effects noted above, and although the details of the replacements are slightly different in some respects, the general story is similar. Replacement of anhydrite by polyhalite in the German salt deposits has also been described (e.g. Lueck, 1913).

Van't Hoff (1912, pp. 280, 322–23) showed that solutions rich in potassium and magnesium sulphates can change gypsum and anhydrite into polyhalite, and suggested that chloride solutions might also effect this change. Schaller and Henderson (1932, p. 72) tentatively favoured chloride solutions as being more likely to dissolve anhydrite. Cunningham (1934) states that two beds of polyhalite near the base of the upper salt are practically continuous over the Texas-New Mexico salt-basin, and may be due to primary precipitation from sulphate-rich brines. He also states that most of the polyhalite is secondary and occurs in areas near the edge of the basin, where land masses gave a source of $CaSO_4$, and where the sulphate-rich solutions would change gypsum and anhydrite to secondary polyhalite. Mansfield and Lang (1934) give a great deal of data on borehole sequences in the Texas-New Mexico basin, and show that a bed of polyhalite may pass locally into anhydrite or halite and then back to polyhalite. Lateral variation of this type may be expected in the British salt-field, since here also the polyhalite seems to be largely secondary.

IX. THE RELATION BETWEEN MAGNESITE AND DOLOMITE.

Nearly all the rocks of this evaporite bed contain a certain amount of carbonate. In some cases this is dolomite, in others magnesite. It is most unfortunate that the core of this evaporite bed was not properly preserved, and that the distribution of the two carbonates cannot be fully worked out. Some idea of this distribution can be got from the well cuttings and the few specimens of known depth, and although this is not really satisfactory it shows that there is an interesting problem here, which should be studied in detail in any future boring in this part of the salt-field.

Only magnesite, and no dolomite, has been found in the rocks from the halite-anhydrite zone. Both dolomite and magnesite have been found in a rock from the upper anhydrite (4415 feet). No carbonate

is present in the specimen of halite-polyhalite-anhydrite-talc-rock from 4445–47 feet. The polyhalite and polyhalite-anhydrite-rocks contain dolomite, not magnesite. Magnesite has been found in well cuttings a short distance below the polyhalite zone, and it seems likely that the rock with 'nests of micaceous mineral' near the top of the lower anhydrite, mentioned in the detailed log of the boring, is the anhydrite-magnesite-talc-halite-rock found in specimens of unknown depth. A specimen from 4559–61 feet contains dolomite, and the well cuttings indicate that the carbonate of the rocks below this is dolomite.

In general, then, it appears that dolomite is the carbonate of most of the lower anhydrite and of the polyhalite zone. Magnesite is the carbonate of the halite-anhydrite zone and of a layer in the upper part of the lower anhydrite. Both magnesite and dolomite occur in the upper anhydrite.

In the anhydrite-dolomite-magnesite-rock from 4415 feet fine-grained anhydrite is seen to be eating its way into dolomite, while the magnesite occurs as euhedral porphyroblasts cutting dolomite. Brines rich in $MgSO_4$ might, under certain conditions, produce magnesite and anhydrite at the expense of dolomite according to the equation

$$MgSO_4 + CaMg(CO_3)_2 = 2MgCO_3 + CaSO_4.$$

If this were so, magnesite and anhydrite might be the equivalents of dolomite and kieserite ($MgSO_4.H_2O$). Kieserite has not been found in this evaporite, although it might be expected in such a paragenesis. Both kieserite and magnesite are recorded in fair quantity from the Texas-New Mexico potash field by Schaller and Henderson (1932), who found no definite evidence of the presence of dolomite. Kieserite generally forms fairly late in the evaporation series, as does magnesite in the Eskdale boring.

It is odd that the carbonate of the polyhalite zone is dolomite, since magnesite apparently occurs both below and above this zone. The polyhalite is believed to be almost entirely, if not entirely, secondary, due to metasomatic replacement of halite and anhydrite. The dolomite in the polyhalite-bearing rocks is very similar to that in the lower anhydrite, and is believed to have suffered no change in the conversion of anhydrite to polyhalite. It appears possible that the lower anhydrite represents a fairly normal sequence, with dolomite as the earlier carbonate and magnesite (possibly derived from dolomite) in the upper part. A freshening of the water near the top of the lower anhydrite may have then interrupted the sequence and caused precipitation of

dolomite again with anhydrite; most of this second layer of anhydrite-dolomite-rock being converted to polyhalite-bearing rock with the original dolomite unchanged, by the action of later brines. A second freshening of the water could produce the upper anhydrite, with dolomite later giving place to magnesite as the brines became richer in $MgSO_4$.

The above suggestions must be considered as tentative. Much more definite information is needed on the distribution of the carbonates here, but there is an interesting problem, which should be reconsidered when more material from this salt-field is available.

No magnesite has been recorded from other parts of this salt-field. Dunham (1948, p. 219) has particularly searched for this mineral in the material from other borings, and has found that the carbonate of these is dolomite; these other borings were put down nearer the edge of the salt-field, where no potash salts have been found, and this again indicates that magnesite occurs fairly late in the evaporation sequence.

There is one other question: how much of the carbonate represents a primary precipitation and how much is due to secondary replacement? It seems likely that much of the dolomite associated with anhydrite is primary. In some rocks the dolomite shows evidence of recrystallization, especially at the edges of halite cavities, but the small rounded dolomite grains in most of the anhydrite-dolomite-rocks are probably primary. Similarly, the small rounded dolomite grains in the polyhalite-bearing rocks are probably the unaltered primary grains previously associated with anhydrite and gypsum in these rocks. Some of the magnesite appears to have been produced by replacement of dolomite, and replacement of anhydrite by magnesite has been observed in coarse anhydrite-magnesite-halite-rock, but there is no evidence suggesting that all, or even most, of the magnesite was produced in this way. It appears likely that the magnesite of the Texas-New Mexico evaporites was mainly primary since it is often associated with clays (Schaller and Henderson, 1932), and there seems to be no reason why some of the magnesite of the Eskdale evaporite should not have been primary. Much of it, however, must have recrystallized since formation if it is not secondary, as in many cases magnesite plates are found cutting recrystallized euhedral porphyroblasts of anhydrite.

X. THE DISTRIBUTION AND ORIGIN OF TALC

The identification and properties of this mineral have been described above. In the lower evaporite bed the mineral has been found in specimens from a wide depth range. It occurs in small quantity in specimens

from the halite-anhydrite zone. A specimen a few feet from the top of the evaporite bed (4314–16 feet) shows a few flakes of talc associated with halite. It is present in larger quantity in the halite-polyhalite-anhydrite-talc-rock from 4445–47 feet in the polyhalite zone, and a few flakes of the mineral have been found in cavities in other polyhalite-bearing rocks. It also occurs in small quantity in halite cavities in anhydrite-magnesite-rocks and anhydrite-dolomite-rocks of unknown depth, and in considerable quantity in certain layers of the anhydrite-magnesite-halite-talc-rock probably to be referred to 4525–37 feet, near the top of the lower anhydrite. Here the detailed log of the boring shows a layer of 'anhydrite with occasional irregular inclusions of salt (nests of micaceous mineral)'. A few small flakes of talc have also been found in halite cavities in a specimen of brecciated anhydrite-dolomite-rock from 4742 feet, not far from the base of the lower anhydrite. The mineral therefore occurs from the top to near the base of the evaporite bed.

In these rocks talc has been found only where halite is present, or in cavities from which halite has presumably been dissolved out during weathering. The mineral has not been found in massive anhydrite-rocks. In all cases where the halite has been preserved the talc forms thin plates, lying along the halite cleavages and often forming a rectangular network. In the anhydrite-magnesite-talc-halite-rocks the mineral forms such a network, crossing halite cavities and anchored at each side by the surrounding anhydrite. At the edges of the cavities the talc plates are attached to the anhydrite along its cleavages or along intergranular boundaries.

In the upper evaporite bed of the Eskdale boring, talc occurs in considerable quantity in the middle of the chloride zone. This evaporite bed will be described in a later communication, but it is relevant to state here that the talc is again especially associated with halite, and the plates nearly always lie along halite cleavages. In some cases talc has been found between halite grains, and in these cases a series of parallel plates runs from the boundaries along the cleavages of the halite grains on either side.

This boring provides the first published record of talc in evaporites, so far as the writer is aware. However, W. T. Schaller, in a personal communication, has stated that the mineral occurs in the Texas-New Mexico evaporites, and that the mineral described as 'polyhalite fibres (p)' in the legend opposite pl. 23 c (Schaller and Henderson, 1932) has later been identified as talc. Here again the talc lies along the cleavages

of the halite, and along intergranular boundaries. Plates project to a lesser extent along sylvine cleavages.

It is most remarkable that talc should be found in such a paragenesis. In discussing the mode of origin of the mineral the following points must be borne in mind:

The constant association of talc with halite.

The occurrence of talc in all zones where halite is present.

The absence of talc in massive anhydrite-carbonate-rocks.

The almost invariable occurrence of talc along the cleavages of the halite.

The occasional occurrence of talc along intergranular boundaries of halite.

The attachment of talc, at the edges of the halite cavities, along intergranular boundaries, and along cleavages of euhedral anhydrite crystals.

The occurrence of talc along cleavages of sylvine (Schaller and Henderson, 1932, pl. 23 c).

The occasional concentration of talc plates near the edges of the halite grains.

The apparent absence of talc in rocks nearer the edge of this salt-field.

The occurrence of talc along the cleavages and intergranular boundaries of halite strongly suggests that the mineral is secondary, and not a primary precipitate. It cannot have grown before the halite was deposited, as it is not present in massive anhydrite-carbonate-rocks. It must have grown later than the euhedral anhydrite at the edges of the halite cavities, as it is generally attached to this anhydrite along intergranular boundaries or along cleavages. Its occurrence along intergranular boundaries of halite and sylvine shows that in these cases it is later than halite and sylvine—as does the concentration of talc plates near the edges of the chloride grains. In the cases where talc plates occur along the cleavages inside halite grains and not in intergranular boundaries, the talc is almost certainly again secondary, as it is very difficult to believe that talc and halite could grow simultaneously in this orientation. Neither is there any reason to believe that recrystallizing halite could force pre-existing talc plates into positions parallel to its cleavages. Magnesite plates show no tendency to any special orientation in halite. The talc, then, is considered to

have formed later than halite in these rocks, and to be a secondary product.

The Texas-New Mexico occurrence suggests replacement of halite, and to a lesser extent sylvine, by talc. Similar cases are found in the upper evaporite at Eskdale. However, such a replacement would be a very curious one, as there is no common chemical constituent involved. In the Eskdale rocks there is no evidence that talc has formed at the expense of any other mineral. It is true that all the Eskdale rocks contain some other magnesian mineral (dolomite, magnesite, or polyhalite) and that crystalline quartz is present in the talc-bearing rocks of the upper evaporite bed, but there is no evidence whatever that these minerals played any part in the production of talc.

Rather than chemical replacement, some type of mechanical replacement is likely. It is easy to believe that solutions could work their way along intergranular boundaries and deposit talc there. By virtue of its crystalloblastic strength the talc might be able to push its way from these boundaries into the cleavages of adjacent halite grains. In the lower evaporite bed it is common to find talc inside the halite and not in intergranular boundaries. It is possible that under slight stress halite might yield by development of potentially open cleavages rather than by weakening of intergranular boundaries. In that case solutions might gain access to the cleavages more easily than to the boundaries of the grains.

The origin of the solutions has still to be discussed. The constant association of talc with halite would indicate either that the solutions were especially associated with those which deposited halite, or that only halite gave access to such solutions. It would be expected that if the talc-bearing solutions had migrated through these rocks for any appreciable distance, talc would be found commonly in massive anhydrite-carbonate-rocks. Its absence here indicates that solutions capable of depositing talc were especially associated with halite, and were possibly present as inclusions in halite.

There is still the question of the date of formation of the talc. This cannot be decided. There seems no reason why it should not have formed since Permian times, when the evaporites were under a considerable cover of overlying rocks. It would seem more reasonable that talc should form under such conditions, where the temperature might be considerably higher than that existing at the time of deposition of the evaporites. It would be interesting to know the mode of occurrence of talc in halite which has recrystallized since Permian times. In the

halite-anhydrite zone there is evidence suggesting that such recrystallization has taken place. However, in the specimen of halite which shows definite platy parallelism no talc has been seen. Future borings may throw more light on this problem.

It is interesting that talc has not been described from other borings nearer the edge of the salt-field. It occurs in the brecciated anhydrite-dolomite-rock near the base of the Eskdale lower evaporite bed—a position low in the evaporation sequence. A special search for this mineral should be made in the halite-bearing rocks of other borings.

XI. SUMMARY AND CONCLUSIONS.

This communication gives the results of a petrological study of rocks from the lowest of the three Permian evaporite beds passed through by the D'Arcy Exploration Company's boring in 1938–39, near Aislaby, Eskdale, east Yorkshire. Unfortunately very few core specimens of known depth were preserved. This study is therefore based on examination of these few specimens, a large number of specimens of unknown depth collected at the site of the boring in 1942, and a set of well cuttings provided by the D'Arcy Exploration Company.

The evaporite bed is 460 feet thick and is underlain by dolomite. The well cuttings and the detailed log of the boring show that it can be divided into four main zones. There is a thick lower anhydrite zone (248 feet), consisting largely of anhydrite, with inclusions of halite towards the base and top, and with subordinate carbonate. This is followed by a polyhalite zone (85 feet) which has a halite-rich upper part, followed downwards by about 45 feet consisting largely of polyhalite and apparently grading into anhydrite-dolomite-rock at the base. Above the polyhalite zone is an upper anhydrite zone (41 feet) with subordinate halite and carbonate, followed by a halite-anhydrite zone (86 feet) with predominant halite.

The following minerals have been found: anhydrite, celestine, dolomite, gypsum, halite, magnesite, polyhalite, pyrite, quartz, sulphur, and talc. Anhydrite, halite, the carbonates, and polyhalite are the major constituents, and talc has a wide distribution. Early gypsum is represented by pseudomorphs consisting of anhydrite, halite, and polyhalite. The other minerals occur only in small amount.

Detailed petrographic descriptions of the halite-anhydrite-rocks, anhydrite-carbonate-rocks, and polyhalite-bearing rocks are given. This study shows that many of these rocks have suffered large-scale changes

due to replacement and recrystallization since original precipitation. There is evidence of the following replacements:

Dolomite → anhydrite
Dolomite → anhydrite + magnesite
Anhydrite → magnesite
Anhydrite → halite
Anhydrite → gypsum
Anhydrite → polyhalite
Anhydrite → sulphur
Gypsum → anhydrite
Gypsum → halite
Halite → polyhalite

In the polyhalite-bearing rocks evidence suggesting the following replacement sequences is found:

Gypsum → anhydrite → halite → polyhalite
Gypsum → anhydrite → polyhalite
Anhydrite → gypsum → anhydrite → polyhalite

It is probable that most of these replacements took place during the formation of the evaporite, and were due to minerals already deposited becoming unstable as the supernatant brines changed in composition, these minerals being dissolved or reacting with percolating brines to form secondary products.

The replacement of dolomite by anhydrite has probably taken place on a fairly large scale in the basal 20 feet or so of the lower anhydrite zone. There is no evidence to date this replacement, and it seems possible that it may have taken place at almost any time during or after the formation of the evaporite.

The replacement of dolomite by anhydrite and magnesite is suggested by the relations between these minerals in a specimen from the upper anhydrite zone. The distribution and relations of these two carbonates are discussed, and it is suggested that such a replacement might have been effected by brines rich in $MgSO_4$, and that in these evaporites magnesite may be partially equivalent to kieserite. Replacement of anhydrite by magnesite is seen in coarse anhydrite-magnesite-halite-rocks. The magnesite cuts through anhydrite grains which show cataclastic structures, and this indicates that the replacement took place when the anhydrite rock was at least partially solid.

Replacement of anhydrite by halite has been seen in an anhydrite-halite-dolomite-rock from near the top of the lower anhydrite zone, and in rocks from the polyhalite zone. It is impossible to determine the extent of such replacement as so few specimens containing halite have been preserved. This replacement was an early one in the polyhalite-bearing rocks.

The replacements involving gypsum are found in the polyhalite zone. Gypsum was widespread as an early mineral in this zone, and the evidence suggests that some of it was primary, and some derived at the expense of anhydrite at a very early stage in the history of these rocks. It was apparently replaced by anhydrite and halite before the appearance of polyhalite.

It is considered that most, if not all the polyhalite of these rocks is secondary in origin, and was formed by replacement of anhydrite and halite due to the action of potassium- and magnesium-rich brines. These changes probably took place during the formation of the evaporites, as the polyhalite zone is cut off at the top by a massive anhydrite zone apparently containing no polyhalite. The rocks of the polyhalite zone have probably been derived from an original layered series of halite-, gypsum-halite-, and anhydrite-dolomite-rocks.

The small traces of sulphur found in anhydrite-carbonate-rocks have been derived from anhydrite, in the presence of carbonaceous matter.

There is evidence that many of these rocks have suffered at least partial recrystallization since their formation. Evidence of recrystallization is widespread in many anhydrite-carbonate-rocks and halite-anhydrite-rocks. It is considered probable that much of this recrystallization took place at an early stage, as there is very little sign of parallelism of the grains. However, in some anhydrite-carbonate-rocks we find cataclastic textures preceding recrystallization, and in one halite-rock we find platy parallelism of halite grains, suggesting recrystallization under pressure, presumably effected when the rocks were under considerable cover. In the polyhalite zone there is no evidence of recrystallization later than the formation of polyhalite, and this also indicates that the bulk of the recrystallization was early. Recrystallization has accompanied replacement in the latter rocks, excess $CaSO_4$ apparently recrystallizing to form anhydrite porphyroblasts in polyhalite-rock, these porphyroblasts often being attacked by later polyhalite.

Evidence of abundant early gypsum has been found in the polyhalite zone, but there is no evidence to suggest that the anhydrite of the lower anhydrite zone is not primary, except where it has replaced dolomite towards the base of this zone. Gypsum apparently had a transitory existence at a stage near the beginning of chloride deposition, and later changed to anhydrite and halite.

The distribution and origin of talc are discussed. This mineral occurs especially associated with halite, and appears to be of later formation

than the minerals with which it is found. The mineral may have been formed after the evaporite bed had solidified. It was probably due to solutions which were especially associated with halite-bearing rocks and did not travel any appreciable distance. As far as the writer is aware, this boring gives the first published record of talc in evaporites.

List of references.

Cunningham (W. A.), 1934. The potassium sulfate mineral polyhalite in Texas. Bull. Univ. Texas, Bur. Econ. Geol., no. 3401, pp. 833–867.

Dunham (K. C.), 1948. A contribution to the petrology of the Permian evaporite deposits of north-eastern England. Proc. Yorks. Geol. Soc., vol. 27, pp. 217–227. [M.A. **10**–568.]

Fowler (A.), 1944. A deep bore in the Cleveland Hills. Geol. Mag., vol. 81, pp. 193–206, 254–265. [M.A. **9**–312.]

Görgey (R.), 1914. Über die Krystallform des Polyhalits. Tschermaks Min. Petr. Mitt., vol. 33, pp. 48–102.

Guppy (E. M.), 1944. Boracite from a boring at Aislaby, Yorkshire. Min. Mag., vol. 27, pp. 51–53.

Hollingworth (S. E.), 1948. Evaporites. Proc. Yorks. Geol. Soc., vol. 27, pp. 192–198. [M.A. **10**–567.]

Lees (G. M.) and Taitt (A. H.), 1946. The geological results of the search for oil-fields in Great Britain. Quart. Journ. Geol. Soc. London, vol. 101 (for 1945), pp. 255–317.

Lueck, (H.), 1913. Beitrag zur Kenntnis der älteren Salzgebirges. Leipzig, 1913.

Mansfield (G. R.) and Lang (W. B.), 1934. The Texas-New Mexico potash deposits. Bull. Univ. Texas, Bur. Econ. Geol., no. 3401, pp. 641–832.

Posnjak (E.), 1938. The system, $CaSO_4$-H_2O. Amer. Journ. Sci., ser. 5, vol. 35 A, pp. 247–272. [M.A. **7**–288.]

—— 1940. Deposition of calcium sulfate from sea water. Amer. Journ. Sci., vol. 238, pp. 559–568. [M.A. **8**–87.]

Schaller (W. T.) and Henderson (E. P.), 1932. Mineralogy of drill cores from the potash field of New Mexico and Texas. Bull. U.S. Geol. Surv., no. 833, 124 pp., 39 pls. [M.A. **5**–168.]

Tilley (C. E.), 1943. Polyhalite from a depth of 4500 feet in a boring at Aislaby, Sleights, near Whitby. Min. Mag., vol. 26, p. lvii.

Van't Hoff (J. H.), 1912. Untersuchungen über die Bildungsverhältnisse der ozeanischen Salzablagerungen. Leipzig, 1912.

Explanation of Plates XXIX–XXXIV.

Photomicrographs and photographs of evaporites from the lower bed in the Eskdale no. 2 boring, east Yorkshire.

Plate XXIX.

Fig. 13. Porphyroblasts of sulphur in anhydrite-dolomite-rock To the right is a patch rich in carbonaceous matter with small clots of sulphur. × 16.

Fig. 14. Anhydrite-dolomite-rock with coarse fibro-radiate anhydrite, showing the edge of a vein-like mass of anhydrite, and patches of anhydrite developing in dolomite (black). × 15.

Fig. 15. Anhydrite-magnesite-rock. The small needle-like crystals are cross-sections of magnesite plates. The crenulated bedding structure is emphasized by carbonaceous impurity. × 11.

Fig. 16. Anhydrite-magnesite-rock. ×25.

Fig. 17. Coarse anhydrite-magnesite-halite-rock, showing plates of magnesite crossing a halite cavity. The groundmass contains a good deal of secondary gypsum. ×16.

Fig. 18. Anhydrite-magnesite-halite-talc-rock, showing a halite cavity crossed by a network of talc plates. Crossed nicols. ×22.

Plate XXX.

Fig. 19. Talc plates lying along cleavages of halite. The white spots are grains of quartz and anhydrite. Upper evaporite, 3780 feet below surface. Crossed nicols. × 20.

Fig. 20. Halite-anhydrite-polyhalite-talc-rock. Plates of talc lie along halite cleavages, and spear-shaped polyhalite crystals along intergranular boundaries of halite. In the lower part of the photograph, tiny grains of polyhalite are developing at the expense of halite. 4445–47 feet below surface. Crossed nicols. ×10.

Fig. 21. Halite-anhydrite-polyhalite-talc-rock. Pseudomorphs of polyhalite and anhydrite, with centres of halite, after gypsum, embedded in halite. Near the centre is a 'swallow-tail' pseudomorph. A few large twinned polyhalite crystals are enclosed in halite. 4445–47 feet below surface. Crossed nicols. ×19.

Fig. 22. Halite-anhydrite-polyhalite-talc-rock, showing polyhalite-anhydrite-halite pseudomorphs after gypsum. Crossed nicols. ×19.

Fig. 23. Anhydrite-polyhalite-dolomite-rock. The rock is composed largely of anhydrite. Polyhalite is developing along cleavages and intergranular boundaries of the large anhydrite grains at the left-hand side of the photograph. × 25.

Fig. 24. Polyhalite-dolomite-rock. It is believed that the rock was originally composed of anhydrite and dolomite, and that the anhydrite has been completely replaced by polyhalite, the dolomite (black) remaining unchanged and showing indication of original bedding structure. ×16.

Plate XXXI.

Fig. 25. Polyhalite-anhydrite-rock with pseudomorphs after gypsum. The pseudomorphs are composed largely of anhydrite, which is replaced by polyhalite to a varying degree, especially at the edges. At the top left of the photograph is an elongated pseudomorph with very little residual anhydrite. The interstices between the pseudomorphs are composed of fine-grained polyhalite, which has perhaps replaced halite. ×10.

Fig. 26. Polyhalite-anhydrite-rock showing pseudomorphs of anhydrite, partly replaced by polyhalite, after gypsum. The interstices are composed of fine-grained fibrous polyhalite, probably after halite. ×15.

Fig. 27. Polyhalite-anhydrite-rock with zoned pseudomorphs after gypsum. Some of the pseudomorphs show alternate zones of anhydrite and polyhalite. ×10.

Fig. 28. Polyhalite-rock with pseudomorphs of polyhalite after gypsum. The

polyhalite of the pseudomorphs tends to be nearly equigranular, while that of the interstices shows a fibrous structure. Crossed nicols. ×10.

PLATE XXXII.

FIG. 29. Polyhalite-dolomite-rock with pseudomorphs after gypsum. The edges of the pseudomorphs are marked by aggregates of dolomite granules (black). ×10.

FIG. 30. Polyhalite-anhydrite-rock with pseudomorphs after gypsum. The two pseudomorphs contain corroded and partly detached relics of two large anhydrite crystals, in positions of extinction. The groundmass is composed of polyhalite, which tends to be equidimensional in the pseudomorphs and fibrous in the interstices. Crossed nicols. ×18.

FIG. 31. Polyhalite-dolomite-rock with a large secondary anhydrite porphyroblast. × 20.

FIG. 32. Polyhalite-rock showing coarse polyhalite projecting into halite cavities. Crossed nicols. × 16.

PLATE XXXIII.

FIG. 33. Halite-anhydrite-polyhalite-talc-rock. 4445–47 feet below surface. Nat. size.

FIG. 34. Polyhalite-rock, with a layer of halite cavities lined with polyhalite crystals, and a weathered crust of gypsum. Polished vertical section of core ×1¼ diam.

FIG. 35. Polyhalite-anhydrite-rock with zoned pseudomorphs after gypsum. Many of the pseudomorphs show zones of anhydrite (dark) and polyhalite (light). Polished cross-section of core. ×2 diam.

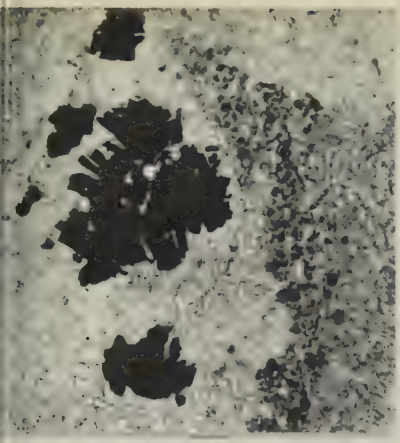
FIG. 36. Polyhalite-anhydrite-dolomite-rock showing anhydrite porphyroblasts in a matrix of fine-grained polyhalite with dolomite. Weathered gypsum crust. Polished cross-section of core. Nat. size.

FIG. 37. Polyhalite-dolomite-rock, with weathered gypsum crust, probably derived from anhydrite-dolomite-rock. Original bedding is indicated by variation in amount of dolomitic and carbonaceous impurity. There is a trace of pseudomorphous structure after gypsum near the top of the specimen. Polished vertical section of core. Nat. size.

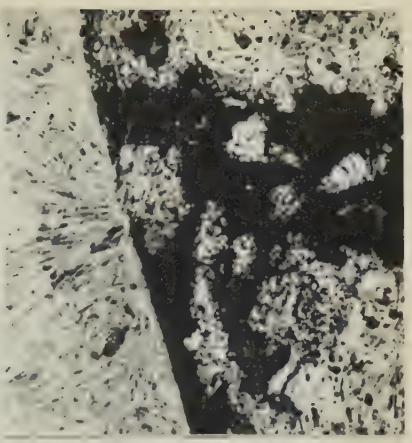
PLATE XXXIV.

FIG. 38. Layered polyhalite-anhydrite-rock, with layers rich and poor in pseudomorphs after gypsum. This is the polished counterpart of fig. 39. The light-coloured layers are composed largely of polyhalite-anhydrite pseudomorphs after gypsum and are believed to have been derived from original gypsum-halite layers. The darker layers consist almost entirely of polyhalite with subordinate dolomite, and are believed to represent original anhydrite-dolomite layers in which a few gypsum porphyroblasts had developed. Polished vertical section of core. Nat. size.

FIG. 39. Counterpart of fig. 38, polished and then etched with water. The polyhalite has developed a thin white decomposition crust of gypsum, while the anhydrite appears darker. It can be seen that the lower pseudomorphous layer is formed largely of 'swallow-tail' twin pseudomorphs after gypsum, showing 'herring-bone' structure marked by alternation of grey anhydrite and white polyhalite (see text-fig. 12). The upper pseudomorphous layer



13

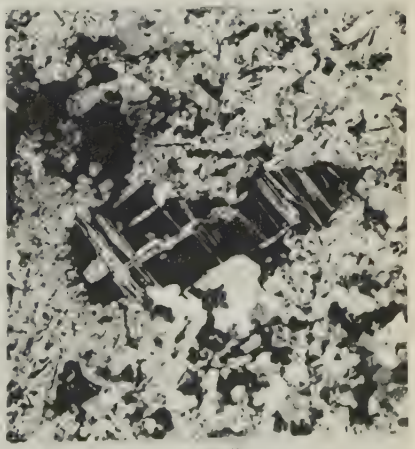


14

15

16

17



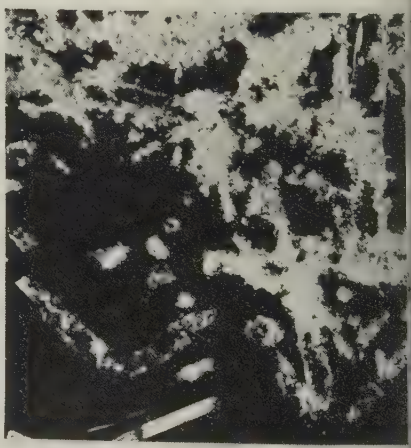
18

F. H. Stewart: Anhydrite-carbonate rocks

19

20

21

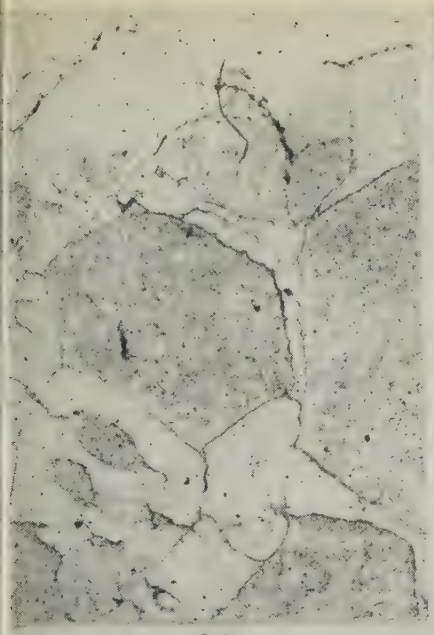


22

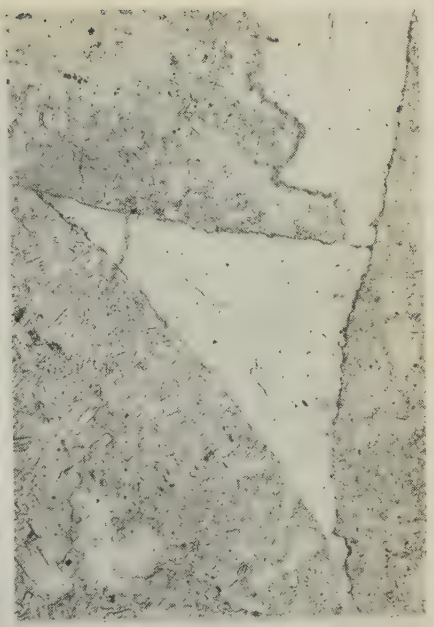
23

24

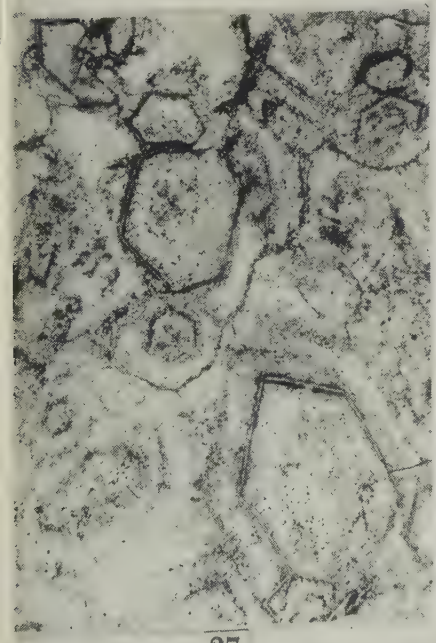
F. H. Stewart: Polyhalite-bearing rocks



25



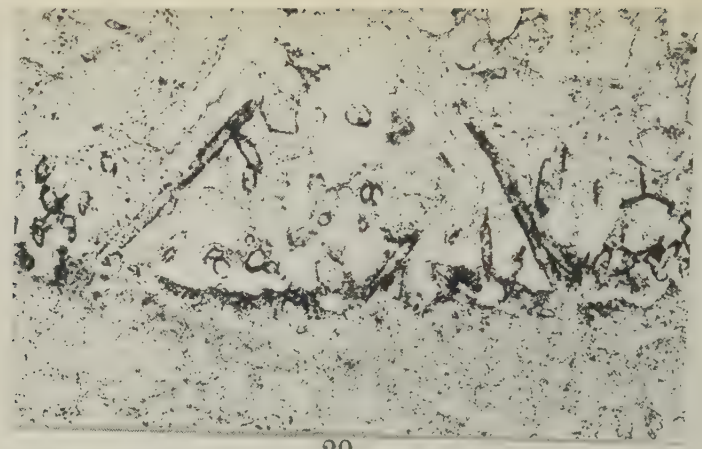
26



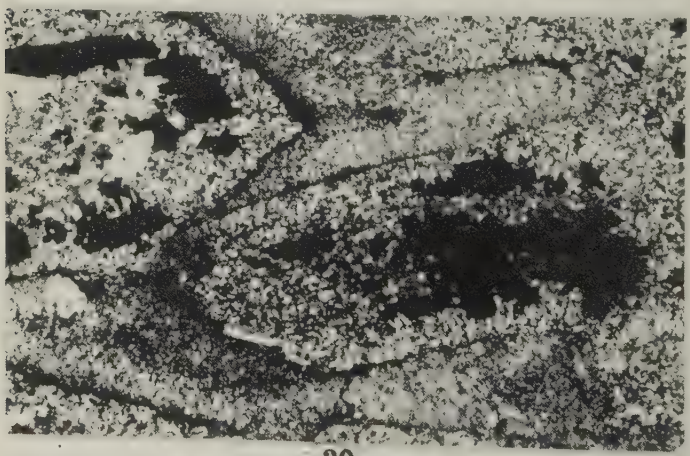
27

28

F. H. Stewart: Polyhalite-bearing rocks



29

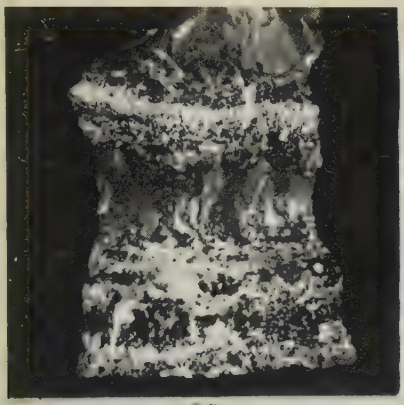


30

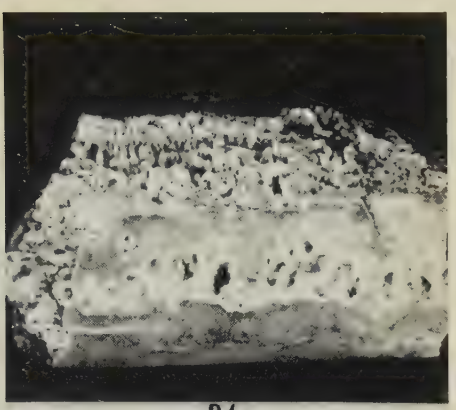
31

32

F. H. Stewart: Polyhalite-bearing rocks

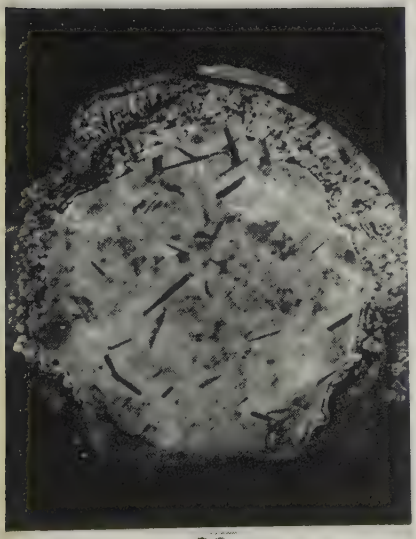


33



34

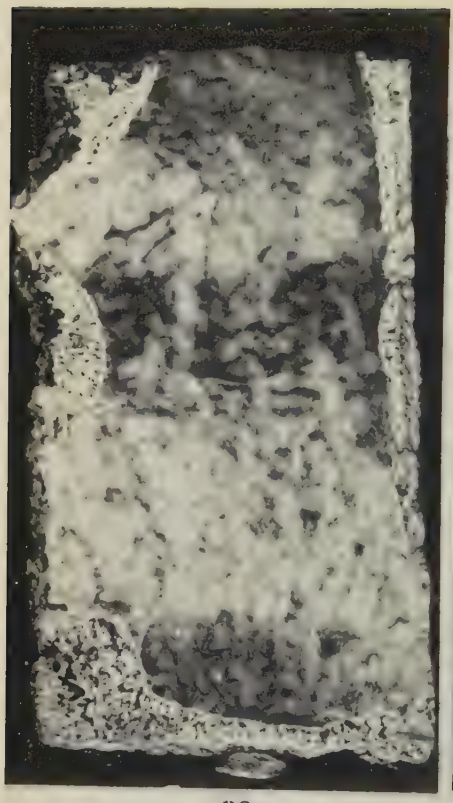
35



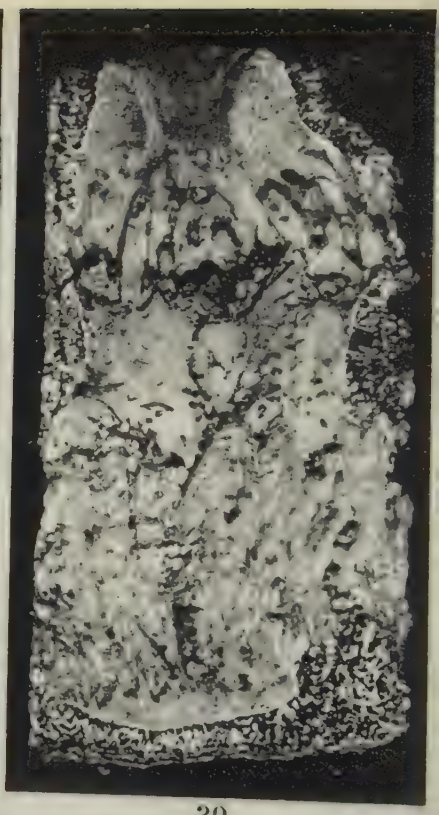
36

37

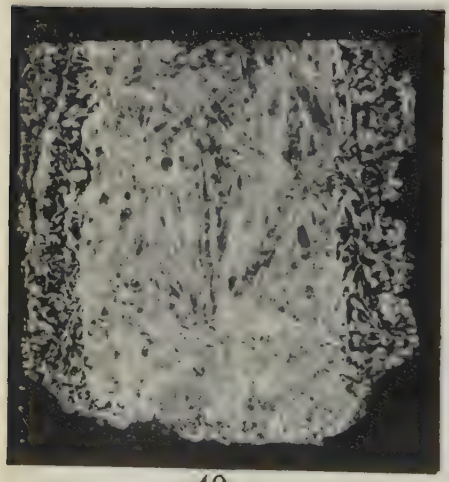
F. H. Stewart: Polyhalite-bearing rocks



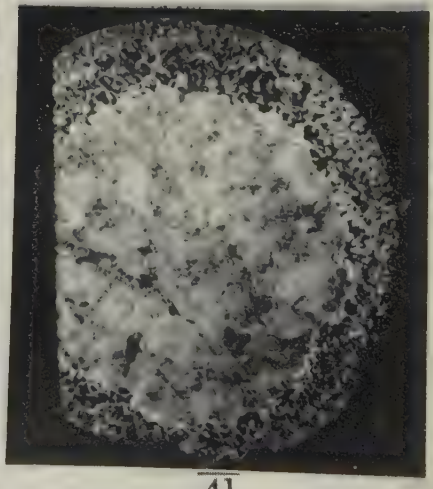
38



39



40



41

F. H. Stewart: Polyhalite-bearing rocks

shows pseudomorphs with outer zones of anhydrite and interiors of polyhalite. Nat. size.

Fig. 40. Polyhalite-rock with well-developed pseudomorphous structure. The structure is emphasized by variation in colour of the polyhalite. This rock is believed to have been derived from an original gypsum-halite-rock. Polished vertical section of core. Nat. size.

Fig. 41. Polished cross-section of the polyhalite-rock of fig. 39, showing cross-sections of pseudomorphs. Nat. size.

A contribution towards the cost of this paper has been received from the Royal Society (Parliamentary Grant-in-aid for Scientific Publications).

The cost of plates XXIX–XXXIV is met by the Miers Memorial Fund.

Cymrite, a new barium mineral from the Benallt manganese mine, Rhiw, Carnarvonshire.

(With Plate XXXV.)

By W. Campbell Smith, C.B.E., M.C., T.D., Sc.D.,
F. A. Bannister, M.A., Sc.D., F.Inst.P.,
and Max H. Hey, M.A., D.Sc.
Department of Mineralogy, British Museum.

[Read March 31, 1949.]

Occurrence and optical data (W. C. S.).

AMONG the specimens collected at the Benallt manganese mine in 1944 by Dr. A. W. Groves and myself was one (B.M. 1944,48) from the 60-foot level in no. 1 ore-body which showed on a face of dark, compact manganese ore colourless plates up to 7 mm. across and about $\frac{1}{2}$ mm. thick. These plates proved to be uniaxial and negative with perfect basal cleavage. Heated in an ignition tube the fragments decrepitated, gave off water, and became pearly, white, and opaque. Qualitative tests showed Ba, Al, and SiO_2 to be present. Preliminary X-ray photographs revealed hexagonal symmetry, but could not be matched with those of any known mineral.

Previously an unidentified white mineral had been noticed closely associated with ganophyllite in a specimen collected in 1944 by Dr. Groves from no. 5 ore-body (B.M. 1944,36). The mineral was first studied in thin section where it appears as a colourless mineral with a perfect and very closely spaced cleavage crossed at right angles by a fibrous structure and by a prismatic cleavage (Pl. XXXV, figs. 3–6). Elongation parallel to the fibrous structure and perpendicular to the perfect cleavage is negative, and birefringence moderate. Measurements on the universal stage indicate that the mineral is uniaxial or nearly so. Subsequently a few small white crystals of this mineral were found in cavities on the specimen. These crystals show a satiny lustre and fibrous structure parallel to their length which is crossed by very frequent basal cleavage cracks (pl. XXXV, fig. 3). The best of these little prisms appear to be hexagonal in form, but only two or three good crystals were found and these only about 1 mm. in length.

At first there seemed nothing to connect this mineral with the colour-

less plates from no. 1 ore-body, but when their refractive indices were found to be very close and their densities nearly equal it became a possibility that the two specimens represent different habits of the same mineral. This was promptly confirmed by an X-ray photograph of a small cleavage fragment from the no. 5 ore-body specimen (B.M. 1944,36).

Refractive indices determined by the immersion method for sodium-light are:

B.M. 1944,48: ω 1·6225, ϵ 1·6125, both $\pm$0·001. Measurement of the birefringence on a single section whose thickness was accurately determined on the universal stage gave 0·0094$\pm$0·0004 for sodium-light.

B.M. 1944,36: the fibrous crystals give lower values, ω 1·6195, ϵ 1·6115 to 1·6140, ϵ varying considerably for different fragments. The birefringence measured directly in white light is 0·008, which agrees with the difference between ω 1·6195 and the lower value of ϵ 1·6115. A single determination for ω (Hg-green) gave 1·624.

With some difficulty sufficient material for a microanalysis was obtained from the colourless plates taken from the specimen (B.M. 1944, 48) from no. 1 ore-body. Part of the face of the specimen carrying the new mineral was cut off closely parallel to the surface. Hand-picking, magnetic and heavy liquid separations, and final hand-picking provided small samples of material of three grades of purity. Two fractions were used for the analyses, one of 20 mg. which still retained a proportion of reddish-brown oxide minerals, and one of 7 mg. almost free from impurities.

The mineral has been named cymrite from the Welsh for Wales, *Cymru* (pronounced kumry).

Chemical analysis (M. H. H.).

Qualitative tests on a few crystals had shown that the mineral is essentially a hydrated aluminosilicate of barium, free from calcium, magnesium, or potassium, but probably containing some sodium; manganese and iron were present in the oxide impurities, but the qualitative analysis had suggested that neither of these was a constituent of the mineral. The quantitative analysis was therefore planned to determine SiO_2, Al_2O_3, BaO, MnO, Fe_2O_3, Na_2O, and H_2O, but in the course of the analysis it became apparent that there was no sodium present, the positive qualitative reaction having been due to an impure sample of perchloric acid.

The less pure sample was divided into two portions. One was gently

ignited, then decomposed with perchloric acid; the filtrate from the silica was precipitated with a small excess of sulphuric acid, and the barium sulphate filtered off, ignited, and weighed; the filtrate was precipitated with 8-hydroxyquinoline (Al+Fe+Mn), and the weighed precipitate dissolved in nitric acid; after destruction of the organic matter, iron and manganese were determined colorimetrically in aliquot parts of this solution, the iron with sulphosalicylic acid and the manganese with periodate. The second portion was treated in the same manner as far as the barium sulphate precipitation, then the filtrate was evaporated to dryness and a sodium determination carried out, as sodium zinc uranyl acetate; sodium was found to be absent.

The purer sample was examined by the first method, but owing to the breakdown of a filter a satisfactory figure for the barium was not obtained, and this constituent is reported by difference.

The density was determined on four carefully selected fragments by suspension in Clerici solution. Owing to the small size of the clean fragments and to the difficulty of wholly eliminating both oxide inclusions and flaws tending to lower the density, the accuracy attained was only about 0·2 %.

TABLE I. Chemical analyses of Cymrite. Col. 1, percentage composition of the purer sample (7 mg.). Col. 2, percentage composition of the second-grade sample (20 mg.). Cols. 1a and 2a, molecular proportions corresponding to Cols. 1 and 2. Col. 3, calculated composition for the formula $BaAlSi_3O_8OH$. Col. 4, empirical unit-cell contents corresponding to Col 1.

	1.	2.	1a.	2a.	3.	4.
SiO_2	44·8	37·65	0·746	0·627	45·79	2·99 Si
Al_2O_3	10·5	14·94	0·206	0·283	12·95	0·82 Al
BaO	[38·5]	31·50	0·251	0·205	38·97	1·00 Ba
H_2O	3·1	5·31	0·172	0·295	2·29	1·38 OH
Fe_2O_3	2·8	9·26	—	—	—	7·53 O
MnO	0·3	0·86	—	—	—	8·91 O+OH
	[100]	99·52	—	—	100·00	—
Sp. gr. (d_4^{16}) ...	3·413 ±0·005	—	—	—	3·46 (calc.)	—

X-ray measurements (F. A. B.).

Transparent cleavage flakes of B.M. 1944,48 identical with material used for optical and chemical work were oriented to give rotation and Laue photographs. They show that the mineral is hexagonal with six planes of symmetry parallel to the [0001] axis and the unit-cell dimensions given by rotation photographs about $[10\bar{1}0]$, $[11\bar{2}0]$, and [0001] are a' 5·33, c 7·67 Å. using copper $K\alpha$ radiation λ 1·5418 Å. These values

together with the specific gravity and chemical analysis yield as unit-cell contents $BaAlSi_3O_8(OH)$ (table I, col. 4).

Well-exposed rotation photographs of the mineral show, in addition to the main layer-lines, additional weak layer-lines that reveal a larger unit cell with $a = 8a' = 42{\cdot}6$ Å. Additional layer-lines, however, are not found on corresponding photographs about the [0001] axis. The weak layer-lines observed on both $[10\bar{1}0]$ and $[11\bar{2}0]$ photographs are satellites to the main layer-lines and not every level in the reciprocal lattice is represented. Each of the main layer-lines of oscillation and rotation photographs about the $[10\bar{1}0]$ is flanked on both sides by weak layer-lines, the observed sequence corresponding to a 42·6 Å. being $\underline{0}$, 1, 7, $\underline{8}$, 9, 15, $\underline{16}$, 17, &c., those underlined being the equator, first and second layer-line corresponding to the pseudo-cell with a' 5·33 Å. Photographs about the $[11\bar{2}0]$ axis show the sequence $\underline{0}$, 1, 2–6, 7, $\underline{8}$, 9, 10–14, 15, $\underline{16}$, 17, 18, &c., corresponding to the cell dimension $\sqrt{3}a = 73{\cdot}9$ Å. The larger unit cell appears therefore to possess hexagonal symmetry like the pseudo-cell.

X-ray powder data for the mineral are given in table II (pl. XXXV, fig. 1), and it is of interest that all the lines observed can be indexed with certainty with the exception of a very weak one at 2·11 Å. which presumably is an extra reflection that can be referred to the true unit cell with a 42·6 Å. Only photographs of well-oriented single crystals reveal the extra spots of subsidiary layer-lines.

Subsidiary layer-lines corresponding to large unit-cell dimensions have also been observed by one of us for sartorite[1] and by S. H. Chao and W. H. Taylor[2] for intermediate members of the plagioclases close in composition to labradorite. It is, however, exceptional for the extra layer-lines to be restricted to weak 'ghosts' flanking the equator and main layer-lines of the pseudo-cell. The phenomenon can be resolved into a regular periodic variation of the atomic scattering factor with frequency corresponding to $8a'$ superposed upon the main pseudo-cell repeat of a'. The optical analogy has been already worked out with specially ruled diffraction gratings by Sir Lawrence Bragg and H. Lipson[3] who were seeking an explanation of the 'ghosts' observed close to the main powder lines of the alloy Cu_4FeNi_3.[4]

[1] F. A. Bannister, A. Pabst, and G. Vaux, Min. Mag., 1939, vol. 25, p. 264.

[2] S. H. Chao and W. H. Taylor, Proc. Roy. Soc. London, Ser. A, 1940, vol. 176, p. 76. [M.A. **8**–13.]

[3] Sir Lawrence Bragg and H. Lipson, Journ. Sci. Instruments, 1943, vol. 20, p. 110 (see particularly figs. 5a and 5b, p. 112).

[4] Vera Daniel and H. Lipson, Proc. Roy. Soc. London, Ser. A, 1944, vol. 181, p. 378.

TABLE II. X-ray powder data for cymrite (B.M. 1944,48)
a' 5·33, c 7·67 Å. (pseudo-cell).

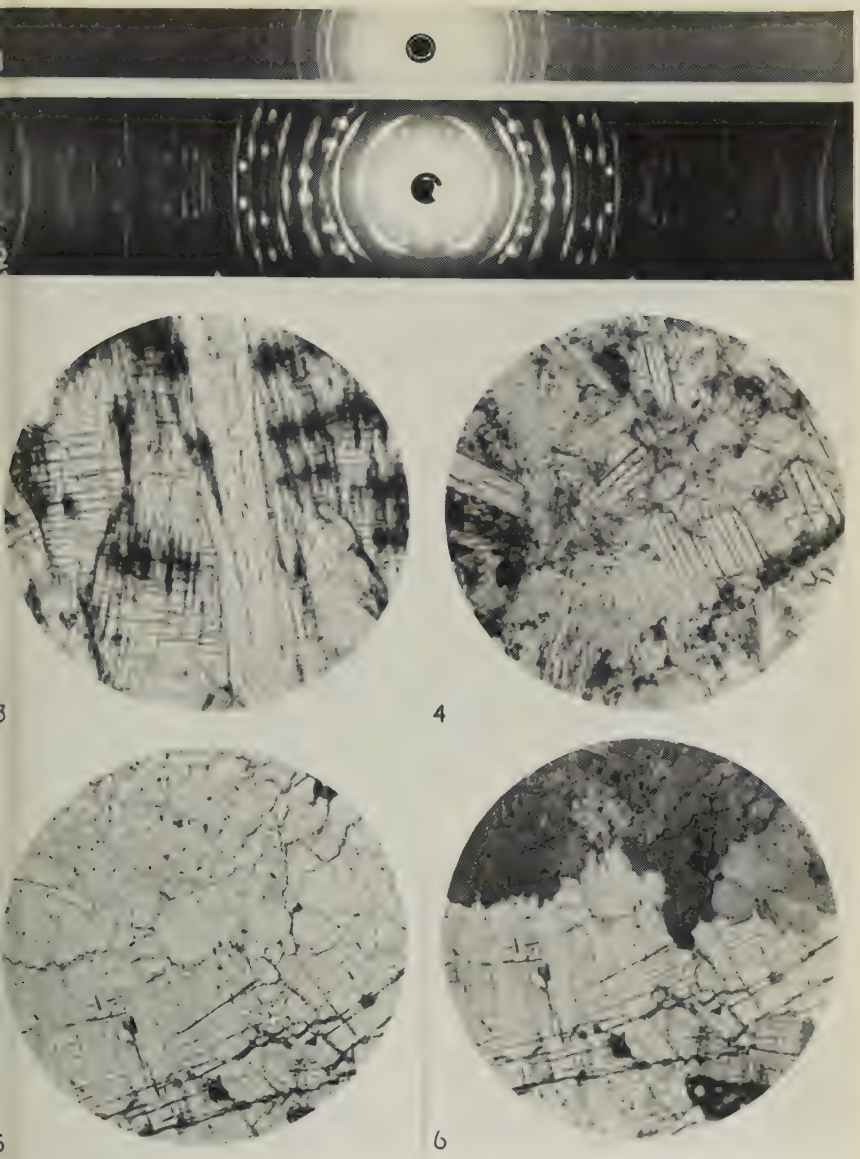
2r. cm.	Intensity.	Spacing Obs. Å.	Calc. Å.	Index.	2r. cm.	Intensity.	Spacing Obs. Å.	Calc. Å.	Index.
1·20	s	7·7	7·67	0001	6·24	w	1·544	1·539	$30\bar{3}0$
2·00	vvw	4·6	4·62	$10\bar{1}0$	—	—	—	1·534	0005
2·35	vs	3·95	3·96	$10\bar{1}1$	6·64	w	1·468	1·472	$10\bar{1}5$
3·16	vs	2·95	2·95	$10\bar{1}2$	6·72	vw	1·452	1·441	$21\bar{3}3$
3·50	s	2·67	2·67	$11\bar{2}0$	7·32	vw	1·341	1·333	$22\bar{4}0$
3·64	vw	2·57	2·56	0003	7·45	vw	1·324	1·319	$30\bar{3}3$
3·70	vw	2·53	2·52	$11\bar{2}1$	7·73	w	1·283	1·280	$31\bar{4}0$†
4·06	w	2·32	2·31	$20\bar{2}0$	—	—	—	1·278	0006
4·20	m	2·24	2·24	$10\bar{1}3$	—	—	—	1·277	$20\bar{2}5$
4·25	m	2·21	2·21	$20\bar{2}1$	7·81	vw	1·269	1·263	$31\bar{4}1$
–	—	–	2·19	$11\bar{2}2$	—	—	—	1·259	$22\bar{4}2$†
4·46*	vw	2·11	—	—	8·05	vvw	1·236	1·233	$10\bar{1}6$
4·76	w	1·990	1·978	$20\bar{2}2$	8·19	vw	1·219	1·214	$31\bar{4}2$
4·94	mw	1·920	1·918	0004	8·31	vvw	1·206	1·200	$30\bar{3}4$
5·14	m	1·849	1·845	$11\bar{2}3$	8·74	w	1·155	1·154	$40\bar{4}0$†
5·35	vw	1·783	1·772	$10\bar{1}4$	—	—	—	1·153	$11\bar{2}6$
5·60	mw	1·705	1·701	$21\bar{3}1$	8·80	vw	1·149	1·152	$21\bar{3}5$
6·04	mw	1·594	1·588	$21\bar{3}2$	9·02	vvw	1·126	1·119	$20\bar{2}6$
6·15	w	1·565	1·557	$11\bar{2}4$	9·34	vvw	1·096	1·096	0007
							–	1·094	$22\bar{4}4$

* An extra reflection from the large unit cell.

† Spots corresponding to these indices are either very weak or cannot be observed on rotation photographs of cymrite about $[10\bar{1}0]$, $[11\bar{2}0]$, and [0001].

The above data were obtained from an X-ray photograph of powdered cymrite taken with filtered copper radiation λ 1·5418 Å. in a cylindrical camera 6 cm. diameter. Relative intensities are given as vs very strong, s strong, ms medium strong, m medium, mw medium weak, w weak, vw very weak, vvw very very weak.

The chemical composition, unit-cell dimensions, and powder data distinguish the new mineral from all other known barium aluminosilicates: celsian, paracelsian, hyalophane, and the recently described barium-felspar banalsite, from the same locality. The pseudo-cell edge a' 5·33 Å. closely approaches, however, the values of a for certain other substances that crystallize with hexagonal symmetry, particularly barium aluminate $BaAl_2O_4$, a 5·21, c 8·76 Å.; kalsilite $KAlSiO_4$, a 5·17, c 8·76 Å.; and β-tridymite, a 5·03, c 8·22 Å. The c dimension of the new mineral is, however, 7·67 Å. and possibly results from a linking of SiO_4 tetrahedra by edges along the [0001] axis, whereas in all three above-mentioned substances the AlO_4 and SiO_4 tetrahedra have their bases parallel to (0001). Moreover, no halvings have been observed for X-ray diffractions from single crystals of cymrite, whereas the odd orders from (0001) are missing both for barium aluminate and kalsilite. The new



W. Campbell Smith, F. A. Bannister, and M. H. Hey: Cymrite, a new barium mineral from Wales

mineral has therefore a new crystal-structure probably of a very simple framework type which it is hoped to publish in the near future.

Some X-ray photographs of single-crystal flakes of the mineral before and after heating to known temperatures were also taken to study further the property of decrepitation on heating, already referred to. The white, opaque plates obtained by heating the mineral in a bulb-tube revealed a polycrystalline texture. Each one yields a flecked powder photograph with sharp well-defined (0001) spectra but with all other spots considerably broadened (Pl. XXXV, fig. 2). A single crystal plate heated to 500° C. for three hours still yields single crystal photographs with a small degree of smearing of the spots into powder lines. This heated material had a lower refractive index of 1·61. A single crystal heated to 700° C. for six hours decrepitated into a large number of very thin flakes with n 153. Each flake still gives single-crystal diffractions after long exposures and it seems probable that the polycrystalline plates (pl. XXXV, fig. 2) result from a shattering with evolution of water vapour into a large number of subparallel flakes.[1]

The chemical analyses are not as good as could be desired, but even with a very wide allowance for analytical error the contents of the pseudo-cell, if integral, cannot be other than $BaAlSi_3O_8OH$. The true cell has a volume 64 times that of the pseudo-cell, and it is possible that this longer periodicity may be associated with a small departure from the simple chemical formula; but the subsidiary layer-lines are so weak that any such departure must be quite small, and it is possible that they may be accounted for by a distinction between O and OH.

Explanation of Plate XXXV.

X-ray photographs and photomicrographs of cymrite.

Fig. 1. Powder photograph of cymrite (table I) taken with filtered copper radiation in a cylindrical camera, 6 cm. diameter. (B.M. 1944,48.)

Fig. 2. X-ray photograph of cymrite after heating, taken with unfiltered copper radiation. (B.M. 1944,48.)

Fig. 3. Thin section of specimen from no. 5 ore-body, Benallt mine (B.M. 1944,36), showing basal and prismatic cleavage and opaque oxides. ×70.

Fig. 4. Thin section of the same specimen showing basal cleavage and vertical fibre or cleavage lines. Ganophyllite in the upper half. ×70.

Fig. 5. Thin section of the same specimen showing closely spaced basal cleavage and, in the upper half, an approximately basal section. ×70.

Fig. 6. The same field seen between crossed nicols. ×70.

[1] Flakes after heating to bright redness have n 1·523, a 5·29, c 7·78 Å.; an example of a small change in crystal-structure without change in cell-volume.

Plagioclases from Sultan Hamud, Kenya.

By P. M. Game, B.Sc.

Department of Mineralogy, British Museum.

[Read March 31, 1949.]

THE plagioclase which forms the subject of this investigation was presented by Dr. C. Stansfield Hitchen, director of the Kenya Geological Survey, who has kindly sent the following note of its occurrence:

'The pale-green transparent felspar described in this note was found on the western slopes of a hill named Kioo, about 14 miles due north of Sultan Hamud station, Machakos district, Kenya Colony. From a description given by Messrs. D. Lyall and P. Cull, who found the mineral, it appears to have occurred in a small vein-like pegmatite sandwiched between parallel plates of decomposing mica. Towards the periphery of the enclosing mica plates the transparent felspar graded into opaque cream-coloured felspar of more normal appearance. The clear material was somewhat shattered and broke with many fragments on removal. The occurrence suggests a deuteric or possibly hydrothermal origin. Kyanite-gneisses occur in the vicinity.'

Two lots of specimens were presented, an earlier set in 1940 (registered number, B.M. 1940,27) and a later set in 1944 (B.M. 1944,140). It is necessary to separate the two groups, since both chemical and optical analyses indicate a perceptible difference in anorthite content. In hand-specimens the glassy appearance (sub-conchoidal fracture), perfect transparency, and pale-green colour of this plagioclase combine to give it an unusual appearance. The (001) cleavage is prominent, that parallel to (010) less so. Very few specimens show both cleavages. No macroscopic twinning could be seen.

The results of chemical analyses of a representative specimen from each group is given in table I. The empirical unit-cell contents have been derived from the analysis, the determined values of the specific gravity, and the cell constants by the method outlined by M. H. Hey.[1] Since the calculated number of oxygen atoms in each analysis closely

[1] M. H. Hey, On the presentation of chemical analyses of minerals. Min. Mag., 1939, vol. 25, pp. 402–412.

TABLE I. Chemical analyses.

(*a*) Albite-oligoclase (B.M. 1940,27) (Analyst: H. Tanssky.)

Analysis.		Atomic ratios.			Empirical unit-cell contents.[1]	
SiO_2	64·92	Si ...	1·0809	...	11·46	16·05
Al_2O_3	21·34	Al ...	0·4187	...	4·44	
Fe_2O_3(+FeO)... ...	1·16	Fe ...	0·0145	...	0·15	
MgO	0·07	Mg ...	0·0017	...	0·02	4·00
BaO	0·008	Ba ...	0·0001	...	—	
CaO	2·18	Ca ...	0·0389	...	0·41	
Na_2O	10·15	Na ...	0·3274	...	3·47	
K_2O	0·44	K ...	0·0093	...	0·10	
H_2O+...	0·09	Mn ...	0·0001	...		—
H_2O-...	0·02	O ...	3·0208	...		32·03
MnO	0·006					
TiO_2	trace					
	100·38					

Sp. gr. (d_4^{20}) ... 2·631±0·010
Molecular composition: Or 2·50, Ab 86·75, An 10·75 %.

(*b*) Oligoclase (B.M. 1944,140). (Analyst: M. H. Hey.)

Analysis.		Atomic ratios.			Empirical unit-cell contents.[1]	
SiO_2	64·10	Si ...	1·0670	...	11·35	16·10
Al_2O_3	22·66	Al ...	0·4446	...	4·73	
Fe_2O_3	0·14	Fe ...	0·0018	...	0·02	
FeO	0·17	Fe ...	0·0024	...	0·02	4·10
MgO	0·25	Mg ...	0·0062	...	0·06	
CaO	3·26	Ca ...	0·0582	...	0·62	
Na_2O	9·89	Na ...	0·3190	...	3·39	
K_2O	0·05	K ...	0·0011	...	0·01	
H_2O+...	0·17	O ...	3·0301	...		32·23
H_2O-...	0·06					
TiO_2	nil					
MnO	nil					
	100·75					

Sp. gr. (d_4^{20}) ... 2·646±0·010
(001) : (010) = 86° 15′
Molecular composition: Or 0·3, Ab 82·7, An 17·0 %

[1] Calculated from the determined values of sp. gr. together with the following cell constants: *a* 8·11, *b* 12·85, *c* 7·16 Å. (S. H. Chao and W. H. Taylor; Proc. Roy. Soc. London; Ser. A, 1938, vol. 176, p. 77. [M.A. **8**–13.] α 93° 45′ (measured value), β 116° 23′, γ 90° 5′ (E. S. Dana, 6th edit. 1892, p. 314).

approaches the accepted total of 32 it has not been considered necessary to recalculate the analyses to this basis. The analyses show that the composition of the first specimen is that of an albite-oligoclase, while the later acquired plagioclase approaches a medium oligoclase. The potash content is small in both specimens. The analyses also demonstrate the absence of the carnegieite molecule.

Table II gives the results of the optical determinations for both felspars. Refractive indices were determined on polished surfaces with a previously calibrated Abbe-Pulfrich refractometer in sodium-light. Optic axial angle measurements and the relationship between the morphological and optical direction were determined on the universal microscope stage.

TABLE II. Optical data.

	Albite-oligoclase (B.M. 1940,27).	Oligoclase (B.M. 1944,140).
α	1·5314 (Na)	1·5351 (Na)
β	1·5355	1·5393
γ	1·5408	1·5437
2V	82½(+)	89(+)
α' : (001) on (010) cleavage flakes ...	—	11½°
α' : (010) on (001) cleavage flakes ...	—	2½°

Comparison of optical data with previously published results.—In fig. 1 the refractive indices of the two sodic plagioclases described in this note are compared with values obtained by earlier investigators.[1] The figure shows that the three values of both the oligoclase and the albite-oligoclase are lower than the mean of previous determinations by 0·0010 to 0·0016. The birefringences, however, are very close to those determined by Duparc and Reinhard. The values of the optic axial angles (obtained by direct measurement) are in almost exact agreement with those given by Duparc and Reinhard, Winchell, and by Köhler.[2]

Projection of morphological reference planes on migration curves.—Although several thin sections of each plagioclase were made, none of these sections showed both the (010) and (001) cleavage. The albite-oligoclase sections showed (010) cleavage traces, while the oligoclase

[1] A. Offret, Bull. Soc. Franç. Min., 1890, vol. 13, p. 654. C. Viola, Zeits. Kryst. Min., 1899, vol. 30, p. 438; 1900, vol. 32, p. 320. F. Becke, Tsch. Min. Petr. Mitt., 1901, vol. 20, p. 71. L. Duparc and M. Reinhard, Mém. Soc. Phys. Hist. Nat. Genève, 1924, vol. 40, p. 134 [M.A. 3 34]. A. N. Winchell, Elements of optical mineralogy, New York, 1933, pt. 2, p. 333. V. B. Meen, Univ. Toronto Studies, Geol. Ser., 1933, no. 35, p. 37 [M.A. 5–439.]

[2] A. Köhler, Tsch. Min. Petr. Mitt., 1941, vol. 53, p. 41. [M.A. 8–313.]

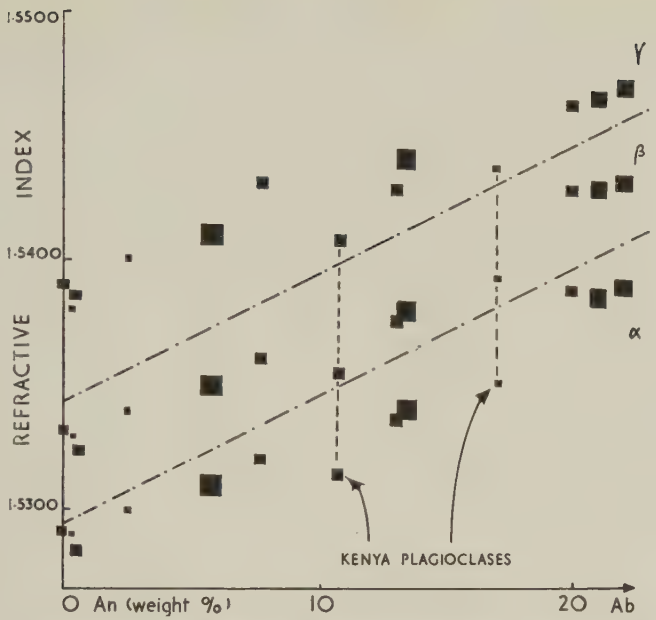


Fig. 1. Refractive index values for analysed albites and oligoclases. Sides of squares are proportional to percentages of orthoclase (0·3–4·0 %). [0·66 mm. = 1 % orthoclase.]

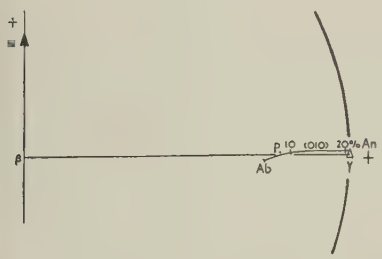


Fig. 2

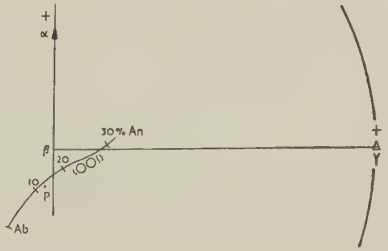


Fig. 3

Fig. 2. Albite-oligoclase (An 10·7 %). Position of pole of (010) cleavage in relation to migration curve of M. Reinhard.

Fig. 3. Oligoclase (An 17 %). Position of pole of (001) cleavage in relation to migration curve of M. Reinhard.

showed (001) traces. The relationship of the poles of these morphological directions to the indicatrix was determined on the stage. The indicatrix axes were then transposed to bring β to the centre in each

instance. The resulting plots were then superimposed on a Reinhard[1] stereogram (20 cm. diameter) in order to compare the positions of the poles (P) of (010) and (001) relative to the appropriate migration curves. Figs. 2 and 3 show these positions. It will be seen that in the case of the albite-oligoclase, the pole of (010) lies practically on the (010) migration curve, and that its position on the curve corresponds to an anorthite content of about 7%. The (001) pole of the oligoclase falls 1 mm. (on the 20 cm. scale) from the corresponding migration curve, and the indicated anorthite content is about 13 %.

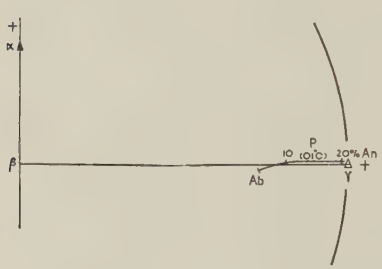


Fig. 4

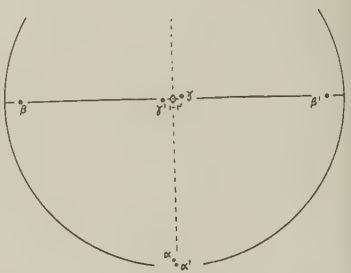


Fig. 5

Fig. 4. Oligoclase (17 %). Position of pole of composition-plane (010) in relation to migration curve of M. Reinhard.

Fig. 5. Oligoclase. Stereogram of twinned individuals with the pole of the composition-plane at centre. The dotted line indicates a possible symmetry-plane.

Very few sections of either plagioclase showed any twinning. In the exceptional instances one set of twin-lamellae was invariably extremely fine (the widest was only 0·027 mm.). The difficulties of obtaining the optical reference directions in these fine lamellae were further increased by the fact that these directions closely approached the corresponding ones in the remainder of the plagioclase (the wide lamellae) and tended, therefore, to be obscured by them when trying to orient the principal optic planes.

For these reasons it was not possible to determine the twin system with certainty. But, by transposal of the plotted poles of the wide lamellae, bringing β to the centre, the transposed pole of the composition-plane was found on the 20 cm. net to lie 3 mm. above the (010) migration curve at a point indicating an anorthite content of An 15 %. Fig. 4 shows the position of this pole in relation to the curve. The composition-plane is, therefore (010).

[1] M. Reinhard, Universal Drehtischmethoden. Basel, 1931, pl. 2. [M.A. 4-435.]

Fig. 5 shows the stereogram of the twinned individuals; in this stereogram the poles have been transposed to bring the pole of the composition-plane to the centre of the projection. The composition-plane itself is thus the plane of projection. The disposition of the poles of individuals 1 (wide lamellae) and 1′ (fine lamellae) suggests the presence of a symmetry plane through α and α'. This indicates a parallel or complex twin. Confirmation of the existence of this type of twinning was obtained by measuring the extinctions of both twin-lamellae in the zone perpendicular to the composition-plane. The extinction angles measured with respect to this plane were unequal (i.e. asymmetrical); the twin-plane is, therefore, not coincident with the composition-plane, and the twinning is not normal.

Owing to the absence of morphological reference directions in the twinned sections it was not possible to determine the twin-law. All that can be said, therefore, is that the twinning is of the parallel or complex type and the composition plane is (010).

Silica percentage as a factor in igneous-rock classification.

By A. K. Wells, D.Sc., F.G.S.
King's College, University of London.

[Read March 31, 1949.]

IN previous editions of Hatch's 'Petrology of the igneous rocks' including the last two, for the revision of which the writer was largely responsible, historical precedent was followed and the main lines of classification were based on variation in the silica percentage. In preparing for the new post-war edition considerable thought has been given to this matter. The weakness of the scheme has become increasingly apparent to the writer, and it is now obvious that no juggling with the selected ranges of silica percentage chosen to delimit the 'acid', 'intermediate', and 'basic' categories can result in a workable, logical scheme. Silica percentage as a basis of rock classification must be abandoned for the reasons discussed below.

The value of the terms 'acid' and 'basic' as applied to rocks is not in question. They conjure up a most useful mental picture involving strong contrasts. On the one hand, the typical acid rock is light coloured, of low specific gravity, and deficient in ferromagnesian silicates. By contrast, the basic rock has a different mineral assemblage, it is dark coloured, of high specific gravity, and rich in ferromagnesian silicates. The commonly accepted mineralogical criterion of acidity is the amount of *free silica* (quartz) in the rock; but acidity is a purely chemical conception, depending on the balance between the acid and basic radicles—the whole of them, not a part only. In typical granites, however, of the total silica, only about one-quarter is free quartz, three-quarters is combined.

As we pass from the basic into the acid rocks, the incoming of quartz marks a significant change in the chemical constitution of the rocks: it shows that the condition of over-saturation with silica has been achieved. Theoretically this should provide one of the fundamental boundaries between rock groups, as Shand has long urged; but actually the solution is not as easy as it appears at first sight. Many intermediate and some basic rocks carry small quantities of quartz tucked away inconspicuously between the essential components. Such rocks are de-

finitely over-saturated, but they are just as clearly not 'acid'. 'Over-saturated' is not synonymous with 'acid'; and in rock-classification *the degree of over-saturation* is more important than the mere fact of over-saturation. As regards mineral composition, all petrologists are agreed that no rock should be termed granite unless quartz occurs in sufficient amount to rank as an *essential* constituent. They agree, further, that a certain amount of latitude is necessary when defining syenite, diorite, norite, gabbro, dolerite, &c., to cover those rocks which, in all essentials fall into one or other of these categories, though they do contain *accessory* quartz.

The immediate problem is to define the boundary between the 'acid' granites, adamellites, and granodiorites on the one hand, and the 'intermediate' syenites, syenodiorites (monzonites), and diorites on the other. Evidently the first requirement must be to reach agreement on the definitions of 'essential' and 'accessory'. Although this is a matter of prime importance, agreement has not yet been reached. Johannsen[1] in his scheme of classification allows a latitude of 5 % free quartz, while Shand[2] is more generous and allows 10 %. Provided it is inexpedient to draw the boundary exactly where discernible quartz first appears, it is of small moment whether the higher or the lower figure is chosen; but it appears to us that there is a good deal to be said in favour of 10 %. The well-known Dresden syenite ('plauenite' of some writers) enjoys a world-wide reputation (which it does not really deserve) of being typical of its kind. It is very widely used for teaching purposes, and many generations of geologists have based their impressions of the typical syenite on this rock, in spite of the fact that much of the apparent orthoclase is seen under the microscope to be red-stained oligoclase in the form of Carlsbad-albite twins. Apart from this, however, the rock is definitely over-saturated, the amount of free quartz varying from 5 or 6 to as much as 12 % (fig. 1, S′ to S″). Therefore some of the Dresden 'syenite' cannot be admitted into this category in any case: it contains more quartz than can be allowed in a syenite and this facies is granitic (actually adamellite). If Johannsen's limit of 5 % were accepted none of the Dresden 'syenite' could be classed as syenite, it would all be granite. This suggests that, as it seems desirable to leave some of this classical rock in the position it has occupied since Werner's time, the limit between essential

[1] A. Johannsen, A descriptive petrography of the igneous rocks. Chicago, 1937, vol. 3, p. 4. [M.A. **6**–483.]

[2] S. J. Shand, Eruptive rocks. 3rd edit., London and New York, 1947, p. 370. M.A. **10**–305.]

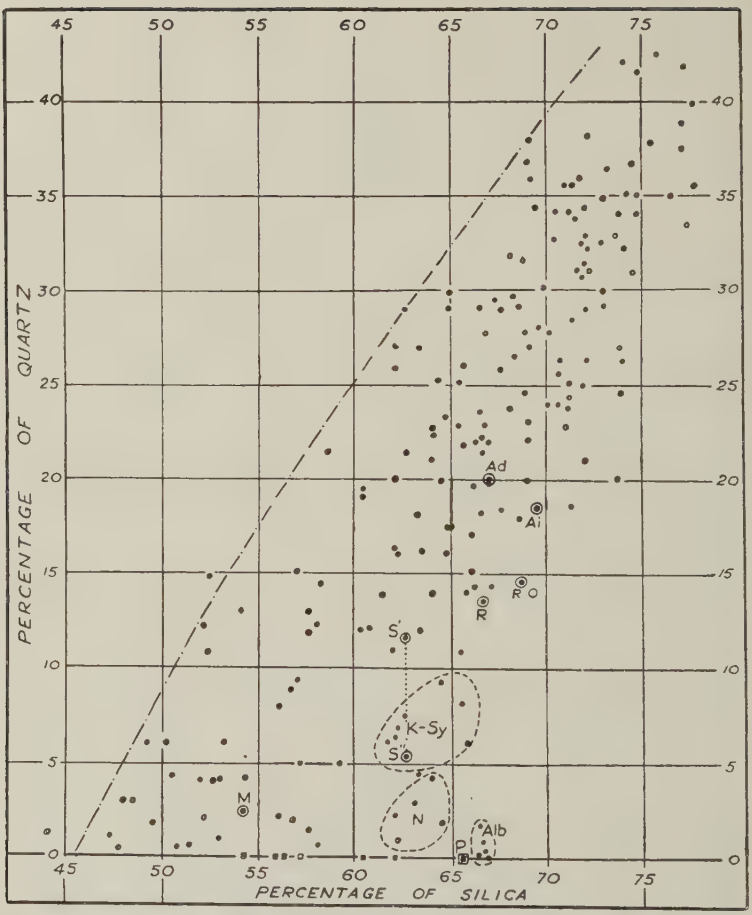


Fig. 1. Plot of the silica percentage and quartz content of certain acid and intermediate igneous rocks. Alb, albitite field; P, perthosite; N, nordmarkite field; M, type monzonite; K-Sy, potassic syenites (kaligranites of Johannsen) S′—S″, 'Dresden syenite'; R, rockallite; RO, riebeckite-orthophyre (Tyrrell); Ai, ailsite (riebeckite-microgranite, Tyrrell); Ad, centre-point of adamellite field. The dash-dot line indicates the upper limit of free quartz.

and accessory, as applied to quartz, should be 10 %. It follows that no rock carrying less than this amount of quartz should be called granite; and conversely, no syenite, syenodiorite, or diorite may contain more than 10 %.

The problem resolves itself, therefore, into selecting a silica percentage which will include in the granites all those rocks containing 10 % or

more of quartz, and at the same time will exclude therefrom all those rocks which contain less than this amount. If the amount of quartz were proportional to the total silica in igneous rocks, the solution would be easy; but there is no such simple relationship, and a solution is impossible.

The publication of Johannsen's encyclopaedic 'Descriptive petrography' has clarified the problem considerably by bringing together and classifying large numbers of first-class analyses, with the corresponding modes. In order to examine the relationship between silica percentage and quartz content, a 'plot' has been made of quartz-bearing igneous rocks recorded by Johannsen, for which analyses and modes are given (fig. 1). The rock-types plotted comprise all kinds of granites including adamellites and granodiorites as well as quartz-bearing syenites, monzonites, diorites, gabbros, and norites. From the diagram two important facts emerge: firstly, rocks containing identically the same amount of quartz may vary in total silica by 15 % or more; and secondly, for a constant silica percentage the amount of quartz may vary from zero to as much as 35 %. The causes of this large variation are sufficiently interesting to warrant examination. In this connexion the group of highly alkaline nearly monomineralic syenites which includes perthosite (P in fig. 1), albitite (Alb), and the hypothetical 'orthoclasite', are important. In the members of this group, the whole of the silica, which ranges from about 66 % to nearly 69 %, is combined. But, as the diagram shows, within this range of silica percentage there are quartz-bearing syenites, 'kaligranites' (Johannsen), adamellites, and granodiorites in variety, some with a quartz content as high as 35 %. Of the various silicates which go to make up these rocks, the alkali-felspars, orthoclase and albite, contain most combined silica, and therefore within this limited silica range, the rock-types richest in these minerals will be poorest in free quartz, and may contain none. There is no question as to the systematic position of these latter rocks: they are syenites by virtue of their mineral content, and in spite of their high silica percentage. If now some of the alkali-felspar is replaced by plagioclase appropriate to these rocks, the combined silica falls, and some free quartz must be added to bring the total silica back to the initial value. A simple calculation shows that with a constant silica percentage of 66, the complete substitution of oligoclase for orthoclase would give a leucotonalite, consisting of 90 % plagioclase and 10 % quartz. But the incoming of the basic silicates, hornblende and especially biotite, produce the same kind of effect though on a much more important scale. In rocks

of these kinds, hornblende contains approximately 48 %, but biotite only 35·5 % of combined silica.[1] It follows that within the 66–69 % total silica range, those rocks at the top of the column are richest in biotite, plagioclase, and free quartz, while those at the bottom are correspondingly poor in these constituents, but rich in alkali-felspars.

Reverting now to the main problem, it is obvious from the diagram that to include among the granites all those igneous rocks with 10 % or more of quartz, the line would have to be drawn at about 52 % total silica. To exclude from the granite category all those quartz-bearing igneous rocks with less than 10 % of this mineral would necessitate drawing the line at about 69 % total silica. Nothing can bring these two lines closer together, and they are equally unsuitable. It is evident that *division on a silica-percentage basis results in bringing together those rocks which it is desired to separate.* The only possible way of retaining this basis of classification would be to devise a sliding scale, with three variables: amount of free silica, ratio of alkali-felspar to plagioclase, and content of coloured silicates. Obviously this would be so complicated as to defeat its own ends: it would be wholly unworkable. Regretfully, therefore, the conclusion is forced upon us that silica percentage must go.

The writer places on record his gratitude to his son for helpful discussion during the preparation of this paper, and for making a fair copy of the diagram.

[1] A. Johannsen, loc. cit., vol. 2, p. 151.

The decomposition of biotite in the soil.

By G. F. Walker, B.Sc., Ph.D.

Macaulay Institute for Soil Research, Aberdeen.

[Read April 9, 1949; Clay Mineral Group meeting at Leeds.]

A NOTICEABLE feature of many of the soils of north-east Scotland is the presence in them of glistening yellow flakes of decomposed biotite. The light-reflecting property of this material catches the eye even though the flakes themselves are often of very small size.

An analogous process to the breakdown of biotite as reported below occurs in the soil-clays of the area, and the present study was undertaken primarily in order to throw light on the mineralogical nature of the clay fractions of the soils, since the large amounts of amorphous material associated with the soil-clay minerals renders less satisfactory the direct approach. The mineralogy of the soil-clays will be dealt with in a separate communication.

REVIEW OF THE LITERATURE.

The changes taking place in the decomposition of biotite have interested mineralogists for many years. Prior to 1934, the terms 'hydrobiotite' (1, 2, 3) or 'vermiculite' (4, 5, 6) were often loosely applied to altered biotite in various stages of decomposition, but in that year Gruner (7) suggested precise definitions on structural grounds and thereby excluded many specimens previously called by these names.

At an early stage, it was established that the weathering of biotite causes an increase in the optic axial angle, a decrease in specific gravity and refractive indices, the disappearance of pleochroism, and a marked colour change from black through golden-yellow to silver and white (8, 9, 10). At the same time, the decomposition was found to be accompanied by a loss of iron, preceded by the oxidation of ferrous to ferric, loss of magnesium, potassium, and sodium, and a gain in water. If the decomposition proceeds far enough, the final product under natural conditions appears to be a kaolinite (9, 11, 12, 13), but at an intermediate stage vermiculite (12), chlorite (14), hydrobiotite (15), or other products (14) may be formed.

A chemical study by Denison, Fry, and Gile (16) of the decomposition of biotite in the soil showed similar trends and indicated that the degree

of alteration is related to the particle size; and Humbert and Marshall (14), studying the genesis of soils from igneous rocks, noted that penetration of water molecules by cracks along cleavage planes in biotite could be followed under the microscope by means of the traces of oxidation left behind.

Hydrothermal alteration of biotite as opposed to natural weathering also tends ultimately to give a kaolinitic end-product (17), although the formation of montmorillonite has been reported on the basis of electron microscope examination (18). The artificial breakdown of the mineral in the laboratory also gives a product with the composition of kaolinite (19, 20, 21, 22), although in this case, if the treatment is sufficiently vigorous, the end-product consists of white flakes of amorphous silica (23, 24, 25). Under the anaerobic conditions obtaining on the sea-floor, glauconite appears to form from biotite (26, 27), but whether this is an ultimate product or merely a stage in the process of breakdown is not clear.

The corresponding changes taking place in the weathering of muscovite have also been examined (16, 28, 29), and although there is no marked colour change in this case, the chemical composition as with biotite tends towards that of kaolinite. It is not known what intermediate minerals, if any, are formed in the weathering of the heptaphyllite. The relative rates of decomposition of muscovite and biotite in the soil appear to be about the same (16), and in spite of some disagreement (6), it is probable that both are among the most resistant of all rock-forming minerals to weathering (21, 30, 31).

SOURCE OF THE MATERIAL.

Most of the weathered biotite flakes examined were obtained from a soil profile in Glen Buchat, Aberdeenshire. The depth of the profile excavated was about 100 cm., and the distribution of flakes of decomposed mica appeared to be fairly even both as regards frequency and range of colour in the various layers of the profile. The very small grain-size of most of the weathered flakes made it difficult to obtain pure samples of uniform material, and attention was therefore concentrated on collecting the few comparatively large flakes which were available. The majority of the flakes obtained were about 1 mm. square and perhaps 0·1 mm. thick, but one or two flakes about ten times this size were found. Various shades of brown and yellow were noted, most of them with a glistening lustre although a few were dull and coated with a brown iron oxide, later shown to be goethite.

A sample of the fresh biotite was obtained from a nearby outcrop of bed-rock—a hypersthene-gabbro in which local segregations of biotite occasionally occur. One of these segregations exposed in a small gully excavated by rain-water was also sampled. This material, which consists of dark brownish crystals showing a yellow lustrous appearance when broken along the cleavage planes, appears to be highly weathered, and crumbles readily in the hand.

EXPERIMENTAL.

X-ray data.—A broad separation of the profile material on the basis of colour was made into three main groups consisting of: (*a*) glistening yellow flakes; (*b*) duller buff-coloured flakes; and (*c*) dull brownish flakes heavily coated with goethite. Representatives of the second and third groups were very scarce relative to group (*a*) which, although it consisted of a considerable range of shades of yellow, was not subdivided further after a preliminary X-ray examination had been made.

X-ray powder photographs of the fresh biotite and the weathered material from the gully differed in certain respects, particularly in the width of the strong basal reflection at 10 Å. This reflection, sharp in the fresh biotite, is notably broadened in the weathered material and its centre shifted from 10·0 Å. to 10·4 Å. The diffraction pattern of the glistening yellow flakes which make up the bulk of the profile material is rather similar to that from the gully; whereas the buff-coloured flakes give an additional basal reflection in the region of 14 Å. as well as at 10 Å.; and the dull brown material, after most of the goethite had been removed by washing in water, gave a sharp reflection at 14 Å. and no indication of one at 10 Å.

On the basis of these results the various stages were placed provisionally in the order:

Order of Weathering.	Description.
0	Fresh black biotite.
1	Dark brown flakes from gully.
2	Glistening yellow flakes from soil profile.
3	Dull buff flakes from soil profile.
4	Dull brownish flakes from soil profile.

The changes taking place in the shapes and positions of the second-order basal reflections during the weathering process are shown in fig. 1, and the complete diffraction data are listed in table I.

TABLE I. X-ray powder data on fresh and weathered biotites from Glen Buchat, Aberdeenshire.

1.		2.		3.		4.		5.		6.	
d.	*I.*	*d.*	*I.*	*d.*	*I.*	*d.*	*I.*	*d.*	*I.*	*d.*	*I.*
—		—		—		13·7	4d	13·6	6	14·0	10
10·0	10	11·0	8	10·9	8	11·8	6d	11·8	3d	—	
–		9·8		9·8		9·8		9·5		—	
–		—		—		—		7·0	1d	7·0	2d
4·60	3	4·56	4	4·57	4	4·57	5	4·56	4	4·56	4
4·23	2	4·23	2	4·17	2	4·17	10	4·15	10	4·15	7
3·70	0·5	3·69	1	3·69	1	—		—		—	
3·53	0·5			—		—		3·53	1	3·50	4
3·34	10	3·35	10	3·36	10	3·36	4d	3·37	2	3·34	5
3·02	0·5	—		3·03	0·5	—		—		—	
2·80	0·5	2·82	0·5	—		—		—		2·80	1
2·73	2	—		2·73	2	2·68	4	2·69	4	2·69	2
2·63	8	2·61	5	2·61	10	2·62	6	2·62	6	2·62	2
2·51	3	2·52	2	2·51	1	—		—		2·53	2
2·44	6	2·43	4	2·42	8	2·43	8	2·44	8	2·44	5
–		—		—		—		—		2·37	2
2·31	1	—		—		—		—		—	
2·27	2	2·27	2	2·28	2	2·24	3	2·24	4	2·25	2
2·23	1	—		2·23		—		—		—	
2·175	4	2·17	2	2·16	6	2·17	4	2·17	4	2·19	2
2·119	0·5	2·11	0·5	—		—		—		–	
2·002	4	1·99	2	2·00	6	2·00	2d	2·00	2d	2·01	0·5d
1·909	2	—		1·92	2	1·92	0·5d	—		—	
1·860	1	–		–		—		—		—	
1·810	2	1·81	4	1·80	4	1·79	2	1·80	2	1·81	0·5d
1·741	1	—		—		–		—		–	
1·716	2	—		–		1·712	5	1·715	5	1·713	4
1·672	6	1·67	3	—		1·686	1	—		—	
1·541	8	1·532	6	1·526	10	1·533	5	1·534	5	1·532	4
1·524	2	—		–		—		—		—	
1·501	1	—		1·505	1	1·502	1	1·505	2	—	
1·476	2	—		—		—		—		—	
1·463	0·5	—		1·462	2	—		1·468	0·5	—	
–		—		—		1·446	0·5d	1·450	0·5	1·449	1
1·435	2	–		—		—		–		1·415	1
1·363	4	1·370	2	1·35	2	—		—		1·373	0·5
1·330	3	–		—		—		—		—	
–		1·322	1	1·322	2	—		–		1·316	1d
1·313	3	—		—		–		—		–	
1·304	4	—		–		—		—		—	
1·284	1	—		—							
1·275	2	-		—		—		—		—	
1·255	2	—		—		—		—		—	

d in Ångström units; *I*, relative intensity estimated visually; Fe-$K\alpha$ radiation; goethite lines present in columns 4, 5, and 6; d = diffuse.

1, fresh biotite. 2, first stage of weathering. 3, second stage of weathering. 4, third stage of weathering. 5, as 4, saturated with glycerol. 6. fourth stage of weathering.

It appears that the first and second stages of weathering are structurally not greatly different from the fresh biotite, since their diffraction patterns differ from it chiefly in respect of the sharpness of the basal reflections. At the same time, considerable colour changes have taken place, from black through dark brown to various shades of yellow, the most extreme examples of which, viz. bright golden-yellow and very pale yellow, give almost identical powder patterns and hence are grouped together in the second stage.

The dull buff-coloured flakes representing the third stage show a diffuse reflection at 14 Å. in addition to the 10 Å. When this material is mixed with glycerol, the 14 Å. reflection becomes appreciably stronger relative to the 10 Å., and weak higher orders appear at 7 Å. and 3·5 Å. This reaction is very interesting because it suggests that *single* layers of glycerol molecules are in certain cases capable of entering between the layers of a 'double-layer' type of mineral (cf. the reaction of glycerol with montmorillonite and halloysite (32)). The buff flakes of the third stage are always associated with goethite, which occurs between the cleavage planes of the flakes and appears when an apparently clean flake is broken along the cleavage.

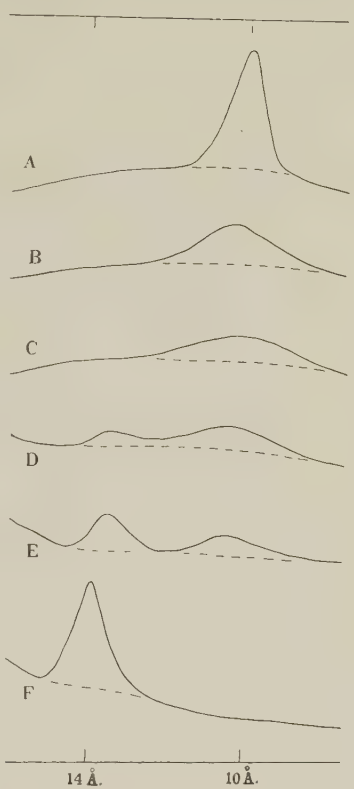


Fig. 1. The shapes of the 10 Å. and 14 Å. reflections at various stages during the weathering of the Glen Buchat biotite. A, fresh biotite; B, first stage of weathering; C, second stage of weathering; D, third stage of weathering; E, third stage after treatment with glycerol; F, fourth stage of weathering (vermiculite).

In the fourth stage the goethite also occurs as a heavy coating on the outsides of the flakes, increasing their apparent size considerably. The flakes of this stage show no sign of a 10 Å. reflection and the appropriate diagnostic tests (33) indicate that the 14 Å. reflection is due to vermiculite. There is no sign of chlorite. None of the flakes examined show any

further increase in basal spacing beyond about 14·2 Å., and it is probable that, if decomposition proceeds farther, it consists in the destruction of the double-layer type of lattice, perhaps with the formation of kaolinite which is present in the clay fractions of the soil.

Optical data.—The α indices of the fresh and weathered biotites were determined by Lindberg's method (34).[1] The indices of each individual stage of the weathering were found to be somewhat variable, due to the degree of alteration to which a particular flake or portion of a flake had been subjected. Not only do different flakes from an apparently uniform sample show variations, but the outside edge of a flake may give a slightly lower value than the core. Data are listed in table II and show that the process of weathering is marked by a general reduction in the indices.

TABLE II. Optical data on the fresh and weathered biotites.

	α.	β, γ.	$\gamma - \alpha$.
Fresh biotite	1·621	1·678	0·057
First stage of weathering	1·624	1·679	0·055
Second stage of weathering	1·598	1·644	0·046
Third stage of weathering	—	1·635	—
Fourth stage of weathering	—	1·630	—

Attention may also be drawn to the difference in refractive index between the first and second stages which is notable in view of the similarity of their powder patterns. A slight increase in the size of the optic axial angle occurs in the first stage of weathering, but thereafter the angle reverts to the size of that in the fresh biotite which is small. Associated with these changes, there is a constant diminution in the definition of the interference figure which is consistently biaxial negative with the acute bisectrix nearly normal to the cleavage planes, as in biotite.

Chemical and physical data.—The data reported in this section are restricted by the scarcity of the profile material. Samples of the fresh biotite and the weathered material from the gully were purified by hand-picking under a lens followed by electromagnetting, after which the material appeared quite pure under the microscope, and X-ray photographs of the analysed samples, over-exposed so as to show up any very faint lines, gave no indication of any of the likely contaminants. The chemical analyses of these samples are given in table III, and so far as they go show trends consistent with those reported by previous

[1] This method consists in sprinkling a number of grains on to sodium silicate in a tacky condition, allowing to dry, and then using those which chance to stand vertically for the measurement of the α index.

workers. Thus, the high proportion of ferrous oxide in the fresh material is almost completely changed to ferric at the first stage; and in addition, magnesia and potash show significant losses balanced by gains in silica

TABLE III. Chemical analyses of the fresh and weathered biotites.

	1.	2.
SiO_2	34·97	38·18
TiO_2	5·64	4·79
Al_2O_3	15·30	15·88
Fe_2O_3	2·81	18·88
FeO	21·23	2·99
MnO	0·16	0·15
MgO	8·83	4·92
CaO	1·09	1·22
Na_2O	0·27	0·46
K_2O	7·17	3·66
H_2O+	3·03	6·70
$H_2O-(105°$ C.)	0·31	2·38
	100·81	100·21

1. Fresh biotite, Glen Buchat, Aberdeenshire; anal. G. Robertson.
2. First stage of weathering; anal. G. Robertson.

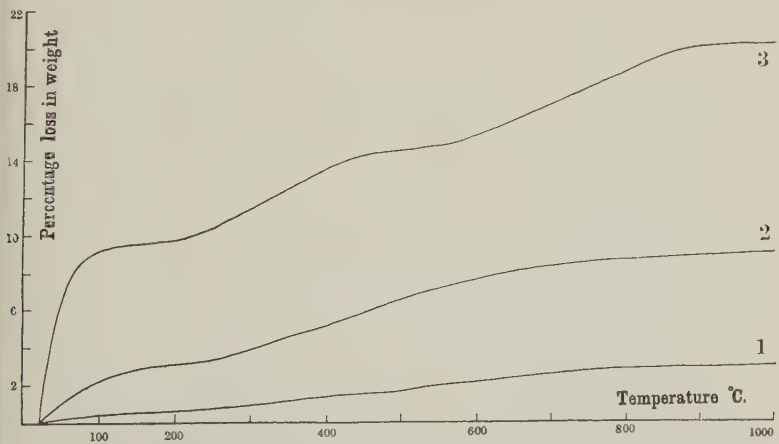


FIG. 2. Cumulative dehydration curves of: 1, fresh biotite, Glen Buchat; 2, first stage of weathering; 3, vermiculite from West Chester, Pennsylvania.

and water. The dehydration data (fig. 2) emphasize the difference in water content between the fresh and weathered biotites, and the curve for a true vermiculite (33) is included for purposes of comparison.

The cation exchange capacity of the fresh biotite (9 milliequivalents per 100 g.) increases on weathering. At the first stage the value is

23 milliequivalents per 100 g., and the very high capacity of hydrothermal vermiculite (33, 36, 40) indicates that this figure probably continues to increase as the weathering proceeds.

Exfoliation tests were made on a number of the weathered flakes both by heat (4) and hydrogen peroxide (37), the latter being much more effective in most cases. The brown flakes of the first stage exfoliated to about ten times their original size with the peroxide treatment and turned a golden-yellow colour. This colour change appears to be wholly due to the mechanical prizing apart of the flakes since there is no associated change in X-ray diffraction pattern or optical properties. The subsequent stages expanded hardly at all with heat or peroxide treatments, and it is probable that they had already largely exfoliated in the soil. The range of yellows represented in stage 2 of the weathering appears to be due at least partly to the degree of exfoliation undergone by the individual flakes; and after exfoliation the dark-brown flakes of the 'first stage' become very similar in appearance to those of the 'second stage'. Ruthruff's (38) exfoliation test for hydrobiotite gave negative results in all cases.

Discussion.

At Glen Buchat the great majority of the weathered biotite flakes in the soil profile are at a relatively early stage of decomposition. A considerable degree of stability at this (the second) stage of soil weathering is suggested by its apparent similarity to the material of Denison, Fry, and Gile (16), who, in a chemical examination of eleven soil profiles, found biotite to be altered to about the same extent in all cases with a potash content approximating 4 %. At Glen Buchat X-ray diffraction enables the process of weathering to be traced beyond this point to the development of a vermiculite and perhaps, by further breakdown, to kaolinite. The final stage, however, is less certain, and in this section we shall consider the process only as far as the vermiculite stage.

It appears from the chemical data that magnesia at first tends to be lost as the weathering proceeds and this is borne out to some extent by other investigations (15, 16). Most published analyses of vermiculites (7) show a high percentage of magnesia but refer exclusively to vermiculites produced by hydrothermal agencies rather than by weathering in the soil. It has not been possible to determine directly whether the soil vermiculite also contains large amounts of magnesium or whether the octahedral positions are occupied by other ions. The large amounts of goethite associated with the advanced stages of decomposition indicate

that much of the iron after its oxidation is removed from the crystal lattice, and replacement of these ions by magnesium from soil solutions rich in this constituent is not unlikely (39).

The (060) reflection on the diffraction pattern of the soil vermiculite, moreover, occurs at 1·53 Å. which is generally regarded as being in the trioctahedral[1] region, and this seems to indicate that the octahedral positions are occupied by divalent ions such as magnesium. The position of the second-order basal spacing of the soil vermiculite is also of interest since it has been shown that the replacement of exchangeable magnesium by other ions in hydrothermal vermiculite may alter the structure of the water layers and hence the height of the unit cell (33, 36, 40). In the diffraction pattern of the soil vermiculite, the occurrence of this reflection at 14 Å. is compatible with the occupation of the exchange positions by magnesium ions although certain other ions, e.g. calcium, cannot be ruled out.

Although these considerations seem to leave the way open to acceptance of the chemical identity of soil and hydrothermal vermiculites, the refractive indices of the two types differ appreciably. Thus the values of the Glen Buchat vermiculite (table II) are significantly higher than those given by Shannon (35) (γ 1·545–1·573) for hydrothermal vermiculite, and seem to indicate a difference in composition between soil vermiculite and vermiculite of hydrothermal origin. It is plain that the final answer to this question must await direct chemical evidence.

Initially, the process of weathering appears to lie in the replacement of the most accessible potassium ions by water molecules which are of much the same ionic size. As this replacement continues towards the interiors of the flakes, the binding between the silicate layers loosens and the spacing of the basal planes increases slightly. Concomitant changes within the silicate layers, such as oxidation of ferrous iron, substitution of hydroxyl for oxygen, and loss of magnesium, take place in order to balance the lattice charges. In this condition, which corresponds to the 'second stage' of weathering, the flakes appear to be fairly stable; but eventually further leaching of potassium from interlayer positions together with replacement of iron in the interiors of the silicate layers by magnesium or other ions from percolating waters reduce the attractive interlayer forces and permit the entry of double layers of water molecules. This latter phenomenon spreads through the crystal layer by layer,

[1] Following the usage of Stevens (41), trioctahedral refers to layer minerals in which all possible octahedral positions are filled, and dioctahedral to those in which only two out of three such positions are occupied. In dioctahedral minerals the (060) reflection usually occurs at about 1·50 Å.

giving first a mixed-layer structure in which increasing numbers of layers become of the vermiculite type.

Just prior to the expansion of an individual layer by natural processes in this way, it seems that glycerol molecules can penetrate to some extent between adjacent silicon-oxygen surfaces and cause expansion. In the case of montmorillonite, glycerol molecules can displace water molecules from between the silicate layers and form a double glycerol layer (32); but in weathered biotite the expansion does not go beyond about 14 Å., so that only one layer of glycerol molecules can be accommodated between a pair of silicate layers. The shortage of material again makes itself felt at this point where the opportunity of further investigation would be particularly welcome; possible alternative lines of approach are, however, available, since a similar phenomenon is found to occur in NH_4-saturated vermiculite (33) and in the 'vermiculite' of the soil clays.

The profile examined is of an intermediate drainage type in which the vertical leaching process is probably fairly active throughout the year. In the clay fractions of the soils of the area, breakdown of a biotite-like clay mineral under free drainage conditions proceeds as above to a vermiculitic product. In very wet conditions, however, i.e. under a permanent or fluctuating water-table, it is not certain that the end-product would be the same, since in the clay fractions of very poorly drained or wet soils of basic origin the weathering of the 'clay biotite' proceeds directly to the formation of a mineral with a freely expanding lattice like montmorillonite,[1] although in other respects its diffraction pattern is similar to the vermiculitic product of the drier soils.

References.

1. F. A. Genth, Amer. Phil. Soc., 1873, vol. 13, p. 397.
2. A. Schrauf, Zeits. Kryst. Min., 1882, vol. 6, p. 350.
3. T. M. Chatard, Amer. Journ. Sci., 1886, ser. 2, vol. 32, p. 375.
4. E. S. Dana, A textbook of mineralogy. 6th edit., 1894, p. 476.
5. C. R. van Hise, Monogr. U.S. Geol. Surv., 1904, vol. 47, p. 1286.
6. F. W. Clarke, Bull. U.S. Geol. Surv., 1924, no. 770, p. 841. [M.A. **3**–64.]
7. J. W. Gruner, Amer. Min., 1934, vol. 19, p. 557. [M.A. **6**–181.]
8. E. Zschimmer, Jena. Zeits. Naturwiss., 1898, vol. 32, p. 551.
9. K. D. Glinka, Trav. Soc. Nat. St. Petersburg, Sect. Géol. Min., 1906, vol. 34, p. 1.
10. N. S. Kurnakov, Ann. Inst. Anal. Phys. Chem. Petrograd, 1924, vol. 2, p. 482.
11. S. B. Hendricks, Amer. Min., 1939, vol. 24, p. 529. [M.A. **7**-496.]
12. P. F. Kerr, Amer. Min., 1930, vol. 15, p. 144. [M.A. **5**–359.]

[1] A mineral taken from the sand fraction of a Banffshire soil and which may be of this kind has been examined by Drs. Muir, Mitchell, Hart, and MacEwan of the Macaulay Institute (unpublished work).

13. V. T. Allen, Amer. Min., 1928, vol. 13, p. 145. [M.A. **3**–487.]
14. R. P. Humbert and C. E. Marshall, Res. Bull. Univ. Miss. Agric. Exp. Stat. 1943, no. 359, p. 1. [M.A. **9**–78.]
15. L. R. Wager, Proc. Yorks. Geol. Soc., 1945, vol. 25 (for 1944), p. 366. [M.A. **10**–74.]
16. I. A. Denison, W. H. Fry, and P. L. Gile, Tech. Bull. U.S. Dept. Agric., 1929, no. 128, p. 1.
17. C. S. Ross and W. F. Foshag, Amer. Min., 1928, vol. 13, p. 153. [M.A. **3**–488.]
18. D. J. Bujor, Neues Jahrb. Min. Monatshefte, Abt. A, 1943, p. 25. [M.A. **9**–82.]
19. A. Johnstone, Quart. Journ. Geol. Soc. London, 1889, vol. 45, p. 367.
20. W. Kunitz, Zeit. Krist., 1929, vol. 70, p. 508. [M.A. **4**–205.]
21. E. R. Graham, Soil Sci., 1940, vol. 49, p. 277.
22. T. Hla, Min. Mag., 1945, vol. 27, p. 137.
23. F. Rinne, Ber. Sächs. Gesell. Wiss., 1911, vol. 63, p. 441.
24. O. Dreibrodt, Diss. Leipzig, 1912, p. 39; Neues Jahrb. Min., 1913, vol. 2, Ref. p.-24-.
25. M. Mehmel, Chem. Erde, 1937, vol. 11, p. 307; Fortschr. Min. Krist. Petr., 1937, vol. 22, p. xlvii. [M.A. **7**-28.]
26. E. W. Galliher, Bull. Geol. Soc. Amer., 1935, vol. 46, p. 1351. [M.A. **6**–288.]
27. V. T. Allen, Amer. Min., 1937, vol. 22, p. 1180.
28. E. Blanck, Journ. Landwirtsch., 1912, vol. 60, p. 97.
29. A. Lacroix, Nouv. Arch. Mus. Hist. Nat. Paris, 1913, vol. 5, p. 255.
30. S. S. Goldrich, Journ. Geol., 1938, vol. 46, p. 17.
31. F. J. Pettijohn, Journ. Geol., 1941, vol. 49, p. 610. [M.A. **8**–237.]
32. D. M. C. MacEwan, Journ. Soc. Chem. Ind., 1946, vol. 65, p. 298; Nature, 1946, vol. 157, p. 159. [M.A. **10**–27, 369.]
33. G. F. Walker, Chapter VII in The identification and structural relationships of clay minerals, edited by G. W. Brindley. Oxford Univ. Press (to be published).
34. M. L. Lindberg, Amer. Min., 1946, vol. 31, p. 317. [M.A. **10**–158.]
35. E. V. Shannon, Amer. Journ. Sci., 1928, ser. 5, vol. 15, p. 20. [M.A. **3**–459.]
36. G. F. Walker, Nature, 1949, vol. 163, p. 726.
37. M. Drosdoff and E. F. Miles, Soil Sci., 1938, vol. 46, p. 391.
38. R. F. Ruthruff, Amer. Min., 1941, vol. 26, p. 478. [M.A. **8**–228.]
39. W. O. Robinson, G. Edginton, and H. G. Byers, Tech. Bull. U.S. Dept. Agric. 1935, no. 471.
40. I. Barshad, Amer. Min., 1948, vol. 33, p. 655. [M.A. **10**–462.]
41. R. E. Stevens, Bull. U. S. Geol. Surv., 1946, no. 950, p. 102.

Illite occurring in decomposed granite at Ballater, Aberdeenshire.

By R. C. Mackenzie, B.Sc., Ph.D., G. F. Walker, B.Sc., Ph.D., and R. Hart, B.Sc., Ph.D.

Macaulay Institute for Soil Research, Aberdeen.

[Read August 26, 1948; Clay Minerals Group at International Geological Congress, London.]

DURING soil survey in the Deeside district of Aberdeenshire, a light greenish-yellow clay-like material was observed penetrating and coating the altered rock along a vein in a granite outcrop freshly exposed in road-widening operations one mile north-east of Ballater. The material occurs in a crush-band in the rock, and the alteration is apparently due to the action of water, but since the band was still highly altered at the base of the exposure (about 25 feet from the surface) it is not certain from the field relationships whether the water was of hydrothermal origin or whether it percolated from the surface.

Samples collected at various points along the crush-band were separated into various particle-size fractions by the usual sedimentation and supercentrifuge technique, using ammonia as the dispersing agent. Samples of particle-size greater than 1·4 μ equivalent spherical diameter were preserved for microscopic examination, while the finer fractions were examined by X-ray, chemical, and thermal methods.

Experimental.

Standard methods were employed for the chemical analyses (1), while the cation exchange capacities were determined by a method similar to that of Jackson and Truog (2). A sintered alumina specimen-holder of capacity 0·2 gram and a ceramic block were used in the differential thermal analysis apparatus, the thermocouple arrangement (chromel-alumel) being identical with that of Grimshaw, Heaton, and Roberts (3). The control mechanism has, however, been made automatic by inserting a constant voltage transformer and a rheostat run by a synchronous motor. Both the temperature trace and the differential trace are recorded on the same chart. The temperatures quoted below are corrected to the temperature of the sample at the peak (3). Dehydration curves were obtained by weighing the material after heating it for one hour at temperatures increasing by 50° C.

Mineralogical data.—The fresh rock is a coarse- to medium-grained pink granite, the tint being due to the colour of the orthoclase felspar. The principal minerals are quartz, orthoclase, oligoclase, and biotite, the biotite being very sparing in amount and the orthoclase in part perthitic. The accessory minerals are zircon, sphene, fluorite, apatite, and iron oxides.

The decomposed rock, mottled pink and light greenish-yellow, crumbles readily in the hand and is confined to a narrow vein running

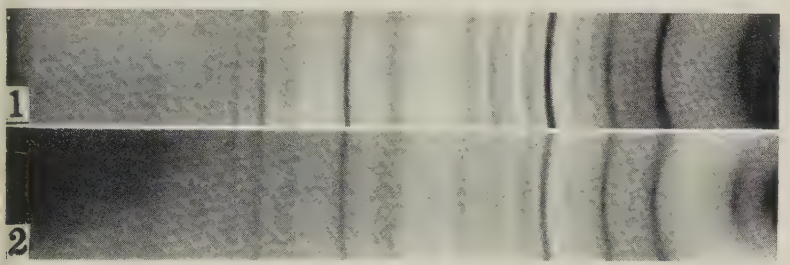


FIG. 1. Powder diffraction photographs of illites: 1, Ballater, $< 1{\cdot}4\,\mu$; 2, Fithian, Illinois.

roughly vertical. The clay mineral, which has a platy character, occurs as a light greenish-yellow soft scale on the decomposed rock and rubs readily off the rock face. It is also found as a network through the decomposed rock and running in cracks in and partly replacing the decomposed felspar. Under the microscope it is nearly colourless. The optical data together with those for illite (4, 5) and hydromuscovite (6) are shown in table I. The figures agree with those for illite rather than those for hydromuscovite, especially in the size of the optic axial angle.

TABLE I. Optical data.

	Illites			Hydromuscovite
	Ballater.	South Wales (5).	Fithian, Ill. (4).	Ogofau, S. Wales (6).
α	1·568	1·572	1·555	—
β	1·590	1·587	—	1·575
γ	1·593	1·600	1·588	1·580
$\gamma - \alpha$ ...	0·025	0·028	0·033	—
2V ...	small	small	small	large

X-ray data.—Powder photographs of the separated material ($< 1{\cdot}4\ \mu$ equivalent spherical diameter) confirm its micaceous character. Comparisons with the published diagrams of other clay micas (table II and fig. 1) reveal a closer resemblance to the Illinois (4) and South Wales

TABLE II. X-ray data.

	Illites							
	Ballater $< 0{\cdot}4\,\mu$		South Wales (5).		Gilead, Ill. (4).		Hydromuscovite Ogofau, Wales (7).	
Indices.	*d*.	*I*.	*d*.	*I*.	*d*.	*I*.	*d*.	*I*.
002	9·9	s	10·0	vs	9·98	s	9·98	s
004	4·9	m	5·0	m	4·97	w	5·02	s
110	4·45	vs	4·46	vs	4·47	s	4·51	m
111	4·28	w	—		—		—	
022	4·10	w	—		4·11	vw	—	
$11\bar{3}$	3·87	m	—		—		—	
023	3·64	mw	—		3·7	vw	3·62	s
$11\bar{4}$	—		—		3·4	vw	—	
006	3·35	vs	3·32	vs	3·31	m	3·34	vs b
114	—		—		3·2	vw	—	
025, $11\bar{5}$	3·09	mw d	2·97	vw	2·98	w	3·09	s
115	2·85	m d	2·80	vw	2·84	vw	2·89	s
$20\bar{2}$	2·56	vs	2·55	vs	2·56	s	2·59	vs
$13\bar{3}$, 202	2·45	mw	2·44	w	2·44	w	2·470	m
204, 133	2·39	m	2·37	mw	2·38	m	2·390	s
$22\bar{1}$	2·235	mw	2·23	w	2·24	m	2·27	w
$22\bar{3}$	—		2·17		2·18	w	2·18	
$20\bar{6}$, 043	2·14	m	2·14	m	2·11	w	2·135	s
0010	1·988	m	1·98	m	1·98	m	1·994	vs
206	1·940	w	—		—		—	
208	—		—		—		1·715	vw
$20\bar{1}\bar{0}$, 312	1·647	m d	1·64	m	1·65	w	1·648	s
060, $33\bar{1}$	1·497	s	1·49	vs	1·50	s	1·505	s
0014	—		—		—		1·416	vw
$33\bar{7}$	—		—		—		1·380	vw
335	1·342	mw d	1·34	w	1·34	vw	1·350	m
							1·336	
400	1·294	m	—		—		1·297	m
402	1·266	w	—		—		—	
0016	1·243	mw	1·24	w	1·24	w	1·245	w

The Ballater illite was photographed with Fe-$K\alpha$ radiation in a 9 cm. camera. *d*-spacings in Ångström units and intensities estimated visually. vs = very strong; s = strong; ms = medium strong; m = medium; mw = medium weak; w = weak; vw = very weak; d = diffuse; b = broad.

illites (5) than to the Ogofau hydromuscovite (7). There are, however, a number of lines on the Ballater illite diagram (e.g. at 4·28 Å. and 3·87 Å.) which do not appear on those of the other illites quoted, although they occur in the muscovite and sericite data given by Grim, Bray, and Bradley (4), and are here indexed accordingly.

Apart from a slight increase in the unit-cell height, heat treatment at 300° and 540° C. has no appreciable effect on the structure, but at 625° C. a few lines of the pattern, viz. those at 3·87, 2·85, and 2·14 Å., tend to

become weaker and at 750° C. they have disappeared completely. At 1000° C. recrystallization to γ-alumina takes place.

Photographs of oriented aggregates treated with glycerol (8) indicate the presence of a very small amount of montmorillonite (1 % or less in the $< 1{\cdot}4\mu$ fraction). A slight tail to the 10 Å. line extending inwards to about 11·5 Å. is also observed on the aggregate photographs and suggests that the illite may be breaking down to form montmorillonite. Decrease in the particle-size of the specimen increases the relative quantity of the latter mineral, so that in the $< 0{\cdot}4\mu$ fraction about 2 % is present, and in the $< 0{\cdot}2\mu$ fraction about 5 % (fig. 2).

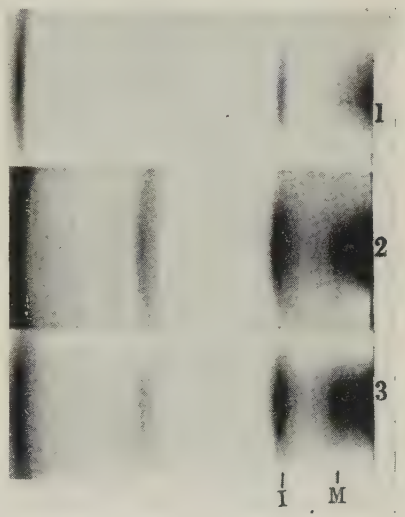


Fig. 2. Aggregate diffraction photographs of Ballater illite: 1, $< 1{\cdot}4\,\mu$; 2, $< 0{\cdot}4\,\mu$; 3, $< 0{\cdot}2\mu$. (I, illite line; M, montmorillonite line.)

Chemical data.—Chemical analyses of three fractions (X-ray diagrams in fig. 2) are listed in table III, together with an analysis of the fresh felspar and published data for other illites (4, 5) and for hydromuscovite (6). Ballater illite, sample 3, was collected from a different part of the section and was red in colour due to the presence of free iron oxide, which is recorded separately in the analysis. Since the calcium content of all three samples was approximately equal to or less than the cation exchange capacity, and since all samples were coagulated with calcium chloride during separation, the analytical figures were corrected for lime, hygroscopic moisture, and free iron oxide, and are recalculated to 100 %. These figures are given in columns 1*c*, 2*c*, and 3*c*. Because of its small montmorillonite content, sample 1 (column 1*c*) is taken for comparison with two other illites, hydromuscovite, and the fresh felspar.

The most significant change in the alteration of the felspar to illite is the almost complete removal of soda. The potash content, however, appears to have been very little affected. An appreciable rise in the alumina, iron, magnesia, and water contents, or decrease in the silica content is also observed.

TABLE III. Chemical analyses.

	1.	2.	3.	1c.	2c.	3c.	4.	5.	6.	7.
SiO_2 ..	49·26	49·01	48·95	51·26	50·36	52·76	51·22	47·55	46·54	66·34
TiO_2 ..	0·05	0·07	0·07	0·05	0·07	0·08	0·53	0·64	0·17	0·04
Al_2O_3 ..	28·97	29·45	26·74	30·15	30·26	28·83	25·91	32·45	36·37	19·18
Fe_2O_3 ..	2·27	2·30	2·44	2·36	2·36	2·63	4·59	0·76	0·72	0·28
FeO ..	0·57	0·70	0·46	0·59	0·72	0·50	1·70	1·85	0·36	0·11
MnO ..	0·04	0·05	0·08	0·04	0·05	0·09	—	—	—	0·00
CaO ..	0·67	0·19	0·91	nil	nil	nil	0·16	0·06	0·22	0·25
MgO ..	1·32	1·52	1·68	1·37	1·56	1·81	2·84	1·70	0·50	0·05
K_2O ..	7·47	7·66	5·44	7·77	7·87	5·86	6·09	6·22	8·06	8·62
Na_2O ..	0·13	0·37	0·16	0·13	0·38	0·17	0·17	1·05	0·46	5·13
H_2O+ ..	6·03	6·20	6·74	6·28	6·37	7·27	7·14	7·73	6·31	0·32
H_2O- ..	3·22	2·78	5·52	nil	nil	nil	1·45	nil	0·52	0·12
	100·00	100·30	99·86	100·00	100·00	100·00	101·80	100·01	100·23	100·44
$SiO_2 : Al_2O_3$ ..			..	2·89	2·82	3·11	3·36	2·49	2·17	—
$SiO_2 : R_2O_3$ ..			..	2·75	—	—	3·02	2·45	2·14	—
$SiO_2 : K_2O$ ..			..	10·32	—	—	13·20	11·96	9·05	—

1–3. Illite, Ballater, Aberdeenshire. Analyst, R. C. Mackenzie. Total in no. 3 includes free Fe_2O_3 0·67 (not determined in nos. 1 and 2). No. 1 of fraction $< 1·4\,\mu$; 2, $< 0·4\,\mu$; 3, $< 0·2\,\mu$.
1c–3c. Ditto recalculated.
4. Illite, Fithian, Illinois. Ref. (4).
5. Illite, South Wales. Ref. (5).
6. Hydromuscovite, Ogofau, South Wales. Ref. (6).
7. Felspar, Ballater. Analyst, R. C. Mackenzie.

The silica-sesquioxide and silica-alumina ratios are similar to those of the other illites and higher than those of hydromuscovite. The ferrous iron, magnesia, and alkali contents, and the silica-potash ratio are, on the other hand, intermediate between those of the illites and those of hydromuscovite, while the water content is similar to that of hydromuscovite.

The formula for Ballater illite on the basis of $24SiO_2$ is: $2·4(K,Na)_2O.1·2MO.8·8R_2O_3.24SiO_2.10H_2O$. This is intermediate between the illite formulae given by Grim, Bray, and Bradley (4) ($2K_2O.3MO.8R_2O_3.24SiO_2.12H_2O$), and by Nagelschmidt and Hicks (5) ($2·5(K,Na)_2O.1·3MO.9·9R_2O_3.24SiO_2.13H_2O$) for alkalis and sesquioxides, but somewhat lower than either in monoxides and water. It differs considerably, however, from the formula for hydromuscovite ($2·9(K,Na)_2O.0·7MO.11·3R_2O_3.24SiO_2.10·8H_2O$) except for the water content.

Because of isomorphous replacements a more valid comparison is probably that on the basis of the ionic composition, taking $O+OH = 48$ (table IV). Here it will be noted that in Ballater illite the relative amounts of O and OH are similar to those in hydromuscovite; the amounts of Si and Al in tetrahedral positions and the total number of ions in octahedral positions are similar to those in Fithian illite; and the amounts of Al in octahedral positions and of alkalis are intermediate between those in Fithian illite and in hydromuscovite.

The cation exchange capacities of samples 1 and 3 (table III) are,

respectively, 23·2 and 42·0 milliequivalents/100 gm. Correcting the latter figure for 5 % montmorillonite of cation exchange capacity 100 m.e./100 gm., the exchange capacity becomes 39 m.e./100 gm., both samples being thus in the illite range (20–40 m.e./100 gm.).

TABLE IV. Chemical (ionic) composition on the basis of (O,OH) = 48.

		Muscovite.	Hydromuscovite.		Ballater Illite.		South Wales Illite.		Fithian Illite.	
K	...	4	2·7	2·9	2·5	2·6	2·0	2·5	2·0	2·1
Na	...	—	0·2		0·1		0·5		0·1	
Ca	...	—	—		—		—		—	
Mg	...	—	0·2		0·5		0·6		1·1	
Fe^{+2}	...	—	0·1		0·1		0·4		0·4	
Fe^{+3}	...	—	0·1	7·5	0·5	7·3	0·1	7·0	0·8	7·3
Al	...	8	7·1		6·2		5·8		4·9	
Ti	...	—	—		—		0·1		0·1	
Al	...	4	4·0	16	2·9	16	3·9	16	2·9	16
Si	...	12	12·0		13·1		12·1		13·1	
O	...	40	37·1	48	37·2	48	34·9	48	35·9	48
OH	...	8	10·9		10·8		13·1		12·1	

Thermal data.—Differential thermal analysis curves of a considerable number of samples from the same exposure were all similar (curves 3, 4, and 5, fig. 3). After the hygroscopic moisture peak there occurs a very broad peak in the region 560–600° C. followed by a sharp, well-defined peak at 713° C. Curves obtained with the same apparatus for illite from Fithian, Illinois, and from South Wales are shown in the same figure (curves 1 and 2, respectively). All the curves are for 200 mg. samples except curve 5 which is for a 170 mg. sample. Correcting the areas of the peaks in curve 5 to 200 mg., the areas of the three peaks at 713° C. are approximately the same, with, if anything, a slight decrease towards the smaller particle-size. The difference in thermal reaction between the type illite and the Ballater material, which is very striking, is discussed below.

Dehydration curves for the same three samples are shown in fig. 4 (nos. 2, 4, and 5) in which curves 1 and 3 are reproduced from the data published by Nagelschmidt and Hicks (5) and by Grim, Bray, and Bradley (4) respectively. Instead of the single 'step' observed in their curves at about 350–550° C. the Ballater material shows two distinct 'steps' at 400–500° C. and 550–650° C., corresponding to the two peaks on the thermograms shown in fig. 3. The first 'step' in these curves apparently increases in size with decrease in particle-size, while the second 'step' decreases.

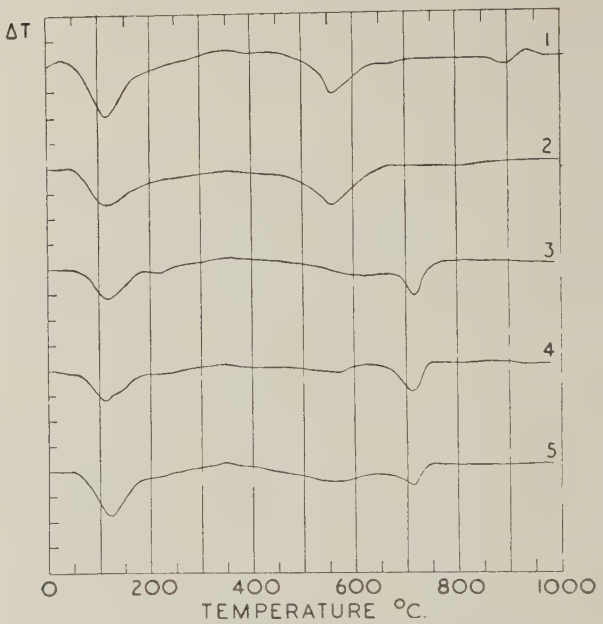


Fig. 3. Differential thermal analysis curves of illites.
1, Fithian, Illinois. 2, South Wales. 3, Ballater, $< 1{\cdot}4\,\mu$.
4, Ballater, $< 0{\cdot}4\,\mu$. 5, Ballater, $< 0{\cdot}2\,\mu$.

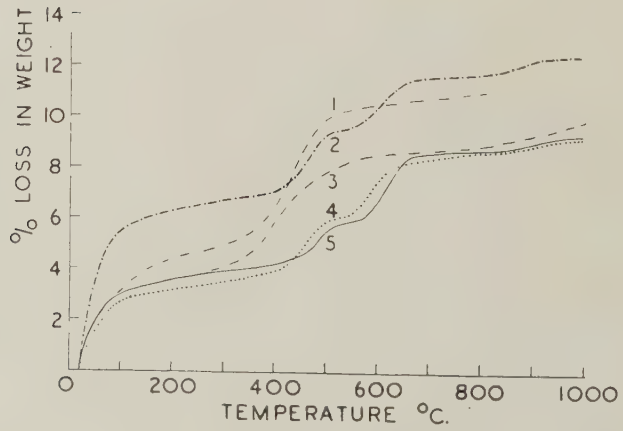


Fig. 4. Dehydration curves of illites.
1, South Wales. 2, Ballater, $< 0{\cdot}2\,\mu$. 3, Fithian, Illinois.
4, Ballater, $< 0{\cdot}4\,\mu$. 5, Ballater, $< 1{\cdot}4\,\mu$.

Discussion.

The X-ray and optical data presented above agree with the classification of the clay mineral as illite rather than as hydromuscovite. The chemical data, while in some respects revealing similarities to hydromuscovite, are, in general, in fairly good agreement with those for illite. The rather ill-defined nature of the term 'sericite', which has frequently been quoted as an alteration-product of felspar (9), makes its use unsuitable for the Ballater mineral. The probable sequence of events in the alteration of the rock would appear to be:

Felspar ⟶ illite ⟶ montmorillonite.

The main points of interest lie in the thermal characteristics of the mineral, which so far as can be ascertained are different from those of any other illite (10). Some similarity may be noted to the thermograms given by Bates (11) for the fine fraction of a mica concentrate from slate, but there the peak at 640° C. is assigned to chlorite of which there is no sign in the X-ray diffraction photographs of our material.

The 713° C. peak might on superficial examination be attributed to montmorillonite: cf. the peak at 700° C. on the thermogram of 'glimmerton' from Sárospatak, Hungary (12). However, the size of this peak (which is, e.g., in curve 3, fig. 3, much larger than would be expected for < 1 % montmorillonite) as well as its relative constancy in area over the range $<$ 1–5 % montmorillonite (fig. 3) rules out this possibility. The apparent very slight decrease in the area of the peak as the particle-size decreases suggests that it is due to the illite. The disappearance of some illite lines in the X-ray pattern after heating in the region 625-750° C. supports this interpretation. The area of the broad peak on the thermogram is very difficult to measure accurately, but there appears to be, generally, a slight decrease with increasing particle-size. This, together with the corresponding decrease in the 400–500° C. 'step' on the dehydration curve, would seem to be associated with the montmorillonite component.

Further support for the above interpretation was obtained from a thermogram of material collected from a different part of the exposure which X-ray examination showed to contain about 20 % montmorillonite and 80 % illite. On this curve the 713° C. peak had disappeared and the broad peak (568° C.) increased very considerably in size, approximately to the extent required by an increase from 5 to 20 % montmorillonite. Increase in the sensitivity of recording showed that the single broad peak observed actually consisted of two overlapping peaks,

one at 568° C. and the other at 713° C. The attribution of the 713° C. peak to illite is thus confirmed.

This conclusion would add still another type of illite to those already distinguished by Caillère and Hénin (13), all these types having similar X-ray patterns, but differing in their differential thermal curves—a position similar to that occurring in the antigorite group (14). In view of the thermal reactions of the Ballater mineral it is evident that caution must be observed in attributing a peak at about 700° C. to the presence of montmorillonite without some additional evidence.

The authors wish to thank Dr. G. Nagelschmidt, St. Austell, for a sample of illite from South Wales, and Mr. D. B. Honeybourne, Building Research Station, for a sample of illite from Fithian, Illinois.

Summary.—A clay occurring in an altered vein in a granite at Ballater, Aberdeenshire, has been examined by optical, X-ray, chemical, and thermal methods. The clay mineral is classified as illite although its thermal data are different from those of any illite so far described. As distinct from the usual illite thermograms, which show a peak in the region 500–600° C., this mineral shows two peaks: a broad one at 550–600° C. and a sharp one at 713° C. A small amount of montmorillonite is found as a contaminant, but this is insufficient to account for the 713° C. peak, while the area of this peak increases as the montmorillonite content decreases. This peak therefore is assigned to illite.

References.

1. I. M. Kolthoff and E. B. Sandell, Textbook of quantitative inorganic analysis. 2nd edit., New York, 1943.
   A. W. Groves, Silicate analysis. London, 1937. [M.A. **6**–483.]
2. M. L. Jackson and E. Truog, Proc. Soil Sci. Soc. Amer., 1939, vol. 4, p. 136.
3. R. W. Grimshaw, E. Heaton, and A. L. Roberts, Trans. Brit. Ceram. Soc., 1945, vol. 44, p. 81.
4. R. E. Grim, R. H. Bray, and W. F. Bradley, Amer. Min., 1937, vol. 22, p. 813. [M.A. **7**–12.]
5. G. Nagelschmidt and D. Hicks, Min. Mag., 1943, vol. 26, p. 297.
6. A. Brammall, J. G. C. Leech, and F. A. Bannister, Min. Mag., 1937, vol. 24, p. 516.
7. G. Nagelschmidt, Zeits. Krist., 1937, vol. 97, p. 518. [M.A. **7**–94.]
8. D. M. C. MacEwan, Nature, 1944, vol. 154, p. 577; Journ. Soc. Chem. Ind., 1946, vol. 65, p. 298. [M.A. **10**–27, 369.]
9. See, e.g. F. H. Norton, Amer. Min., 1937, vol. 22, p. 1; 1939, vol. 24, p. 1; 1941, vol. 26, p. 1; N. P. Peterson, C. M. Gilbert, and G. L. Quick, Econ. Geol., 1946, vol. 41, p. 820; G. M. Schwartz, ibid., 1947, vol. 42, p. 319.
10. S. B. Hendricks and L. T. Alexander, Soil Sci., 1939, vol. 48, p. 257; Russell and Haddock, Proc. Soil Sci. Soc. Amer., 1941, vol. 5, p. 90; Schafer and Russell, Soil Sci., 1942, vol. 53, p. 353; Grim and Rowland, Amer. Min., 1942,

vol. 27, pp. 746, 801; Grim, ibid., 1947, vol. 32, p. 493; Bates, ibid., 1947, vol. 32, p. 625; Grim and Bradley, ibid., 1948, vol. 33, p. 50; Caillère and Hénin, Ann. Agron., 1947, vol. 17, p. 23; Speil, Berkelhamer, Pask, and Davies, Tech. Paper, U.S. Bur. Mines, 1945, no. 664.

11. T. F. Bates, Amer. Min., 1947, vol. 32, p. 625. [M.A. **10**-365.]
12. R. E. Grim and R. A. Rowland, Amer. Min., 1942, vol. 27, p. 746, 801 [M.A. **9**-76.]; for X-ray data see E. Maegdefrau and U. Hofmann, Zeits. Krist., 1937, vol. 98, p. 38.
13. S. Caillère and S. Hénin, Ann. Agron., 1947, vol. 17, p. 23.
14. S. Caillère, Bull. Soc. Franç. Min., 1936, vol. 59, p. 163. [M.A. **6**-475.]

Unusual dolomite from Portsoy, Banff.

By W. T. Harry, B.Sc.

Department of Geology, University College, Dundee,

and E. M. Patterson, M.Sc., A.R.I.C., F.G.S.

Department of Geology, United College, St. Andrews University.

[Communicated by Dr. J. E. Richey; read March 31, 1949.]

A THIN belt of serpentine up to 400 yards wide and about 6 miles long runs SSW. from Portsoy, Banff, and parallel to the general structure lines at that locality. Near Damhead, 1½ miles SSW. of Portsoy, an old quarry has recently been reopened in this belt and worked to a depth of 98 feet for the exploitation of talc. The general association in this quarry, stated in order of quantitative importance, is serpentine, talc, dolomite, the last being present in very minor amount but of an unusual character meriting description. In the following account the particular task of one of us (E. M. P.) has been the preparation of chemical analyses, the other author being responsible for descriptions and discussion.

A foliated olivine-serpentine with massive green, dark and lighter coloured varieties composes by far most of the rock in Damhead quarry. Certain types that may be 'shaved' with a penknife are used as low-grade talc in the roofing-felt industry, others are employed in tile manufacture. Occasional thin chrysotile veins have been observed. The serpentine is highly sheared, good curved slicken sided surfaces being commonly developed. The stronger dislocations are approximately vertical and strike parallel to the outcrop of the serpentine. Talc is developed as impersistent lenticular bodies in vertical crush zones in serpentine. Thick sheaths coating serpentine lenses are common, and pieces of talc up to 6 inches across may be obtained. In general the talc 'veins' broaden downwards. Talc also coats minor shear planes in serpentine. Both white and pale green varieties occur. Disseminated magnetite is present, and is removed before using the talc for refractory purposes in industry.

Dolomite is found from time to time whilst breaking up serpentine blocks in the heart of which it forms masses up to one foot across with irregular margins and no apparent 'feeders'. These occur throughout

the quarry but are exclusively within serpentine, especially where the latter has been sheared into lenses. They are white in colour, opaque, resemble calcite in general appearance, and present large perfectly plane cleavage surfaces uninterrupted across their whole mass and often $\frac{3}{4}$ square foot in area, i.e. each body is a large individual crystal. The mineral has a sub-vitreous lustre, rr' $(10\bar{1}1):(\bar{1}101) = 73° 45'$ and may show secondary twin lamellae. Curved r faces are very rarely found. It does not react with cold dilute HCl, and it scratches calcite easily. Specific gravity 2·86. Powdered and treated with Lemberg's solution it is but faintly stained after 20 minutes.

Two samples selected to be as free as possible from included fragments of serpentine were taken for chemical analysis from a large quantity of material. They were treated with boiling 5 % HCl and gave the following results:

	I.	II.
CaO	30·59	30·53
MgO	21·33	21·10
CO_2	47·21	47·01
Insol. in HCl ...	0·37	0·84
	99·50	99·48

The hydrochloric acid soluble portion was tested for iron by the highly sensitive colorimetric tests using thioglycollic acid and potassium thiocyanate. Only traces were detected, indicating practically no $FeCO_3$. Lead was absent. Spectrographic analyses of the hydrochloric acid soluble portion of each sample were made at the Ministry of Agriculture Research Laboratories, Belfast, by permission of Professor Baskett. The Lundegårdh air-acetylene flame method was used, with the following results:

	I.	II.
BaO	1·15	1·68 %
SrO	0·017	0·018

The high summation when the content of equivalent $BaCO_3$ is added to the results of the chemical analysis is believed due to co-precipitation of part of the barium with the calcium, due to the great excess of the latter. An accuracy of ± 25 % for the barium content is likely and a somewhat higher degree of accuracy in the case of strontium. Of geochemical interest is the high content of soluble barium. The carbonates of calcium and magnesium and the double carbonate dolomite are trigonal, whereas barium and strontium carbonates are orthorhombic. Also of interest is the remarkable purity of the dolomite,

especially compared with other Scottish dolomites in similar as well as other parageneses.

The association serpentine–talc–dolomite is well known and usually referred to metasomatic processes operated by low-temperature solutions. Hess,[1] for example, defines steatitization as 'that process of hydrothermal alteration of an ultrabasic which in its final stages results in the formation of a talcose rock'. Depending on the composition of the active solutions, dolomite may or may not be a by-product of such reactions; though all three minerals may form stable phases under metamorphic conditions corresponding to the green-schist facies. At Damhead, although, from general considerations stated below, the dolomite and talc appear related, if the former had formed as such a by-product it must since have been completely differentiated from its parent, as it occurs only in serpentine. So complete a separation seems unlikely. Again, talc at lower metamorphic temperatures is unstable in the presence of CaO- and CO_2-bearing solutions, being dolomitized. This reaction also cannot satisfactorily explain the Damhead occurrence, since traces, at least, of some half-way stage would be expected had such replacement been effected, but as remarked, the amount of the talc associated with the dolomite is quite negligible. The dolomite is considered to be the result of direct replacement of serpentine by CaO- and CO_2-bearing solutions of unknown origin. If growth had taken place within a cavity, then each early crystal deposited on to walls must have been identically orientated to explain the crystal continuity within each body. Such is not reasonable and is contrary to experience of known cavity fillings. The intricate relations between dolomite and serpentine further indicate replacement, and possibly the lack of free faces during such growth may account for the lack of characteristic curved *r* surfaces. It follows, then, that each dolomite body is a single crystal and may be regarded as a large porphyroblast.

It is here of interest that Eskola[2] has attempted to generalize, assigning most ankerite-poor dolomites to a metasomatic origin and ankeritic varieties characteristically to ore veins. The mineral, as noted, is strikingly pure, the more so considering its environment. An analysis of typical associated green serpentine, kindly lent by Rowebb Ltd., showed Fe_2O_3 7·58 % and FeO 0·71 %. It would seem that this purity may be largely ascribed to dominance of Fe''' in the serpentine which

[1] H. H. Hess, The problem of serpentinization and the origin of certain chrysotile asbestos, talc and soapstone deposits. Econ. Geol., 1933, vol. 28, pp. 634–657.

[2] P. Eskola, Kristalle und Gesteine. Wien, 1946. [M.A. **10**–191.]

on account of its ionic radius was unable to enter the dolomite lattice and therefore cast out, some forming occasional included magnetite grains. In addition to this role of iron, however, serpentine included in and bordering the dolomite is usually paler in colour and therefore, from reference to chemically investigated serpentines, presumably poorer in iron than the surrounding rock, suggestive of leaching by the dolomitizing solutions.

That the Damhead association is of common occurrence suggests in itself that each member may be referred to stages in the same geological process (retrogressive metamorphism). That this latter depended mainly upon metamorphic stress is indicated by the highly crushed nature of the rock at the quarry and by the fact that there is no field association of igneous rock to which the diaphthoresis may be suitably ascribed. Active solutions mobilized by stresses gave rise to the transportation and recrystallization of dolomite at localized centres of lower pressure where the solubility of the carbonates would decline.[1]

This replacement took place at the same time as, or slightly before, steatitization, to account for the absence of similar dolomite masses in the talc lenses, and was most probably not isovolumetric. In conclusion, reference may be made to exposures, particularly near Balmaha, east side of Loch Lomond, in the serpentine belt of the Highland border, where dolomitization of serpentine is associated with faulting.[2]

Acknowledgements.—We wish to thank Mr. Roemmele of Rowebb Ltd., and Mrs. Grant, Secretary of Glitterite Ltd., for material and for affording every facility during a field visit of one of us (W. T. H.). We should also like to record our gratitude to Dr. J. E. Richey and Dr. H. Neumann for reading this account and to Professor D. E. Innes for facilities.

[1] R. E. Gibson, The nature of solutions and their behaviour under high pressures. Scientific Monthly, New York, 1938, vol. 46, pp. 103–119.

[2] J. G. C. Anderson, The geology of the Highland border: Stonehaven to Arran. Trans. Roy. Soc. Edinburgh, 1947, vol. 61, pp. 479–515.

Correlation of the Mohs's scale of hardness with the Vickers's hardness numbers.

By E. Wilfred Taylor, C.B.E., F.R.M.S., F. Inst. P.

Messrs. Cooke, Troughton & Simms, Ltd., York.

[Read June 23, 1949.]

MINERALOGISTS have long been accustomed to describe hardness with the aid of a scale devised by Friedrich Mohs, who lived from 1773 to 1839. The test is qualitative, each mineral in the scale being capable of scratching those that precede it, but the ten minerals have held their ground as a useful representative series with which it is now interesting to compare another method of estimating hardness.

In the metallurgical world hardness is now usually expressed by means of the Vickers's hardness numbers or their equivalent, and the figures are derived from the size of the impression made by a diamond indenter in the form of a four-sided pyramid with the opposite faces worked to an included angle of 136°.

More recently micro-hardness testers have been devised to enable minute impressions to be formed under light loads on small individual crystals of a metallic alloy,[1] and it occurred to the author to obtain hardness figures for the various types of optical glass by means of a scratch test with such an instrument. The intention was to draw a lightly loaded diamond across a polished glass surface and to measure the width of the resulting furrow. This method proved to be promising, but as an experiment a static indenter was also used, and it was discovered that glass was sufficiently plastic to take good impressions, so long as the load did not exceed 50 grams or thereabouts.[2]

The next step was to determine if minerals behaved in the same way, and, although the impressions were not always perfect, it has been possible to construct a comparative table and to assign to each of the minerals in Mohs's scale a Vickers's hardness number.

It was realized that the minerals belong to various crystal classes and that the hardness figures obtained might, like the scratch hardness,

[1] E. W. Taylor, Micro-hardness testing of metals. Journ. Inst. Metals, 1948, vol. 74, p. 493.

[2] E. W. Taylor, Nature, 1949, vol. 163, p. 323.

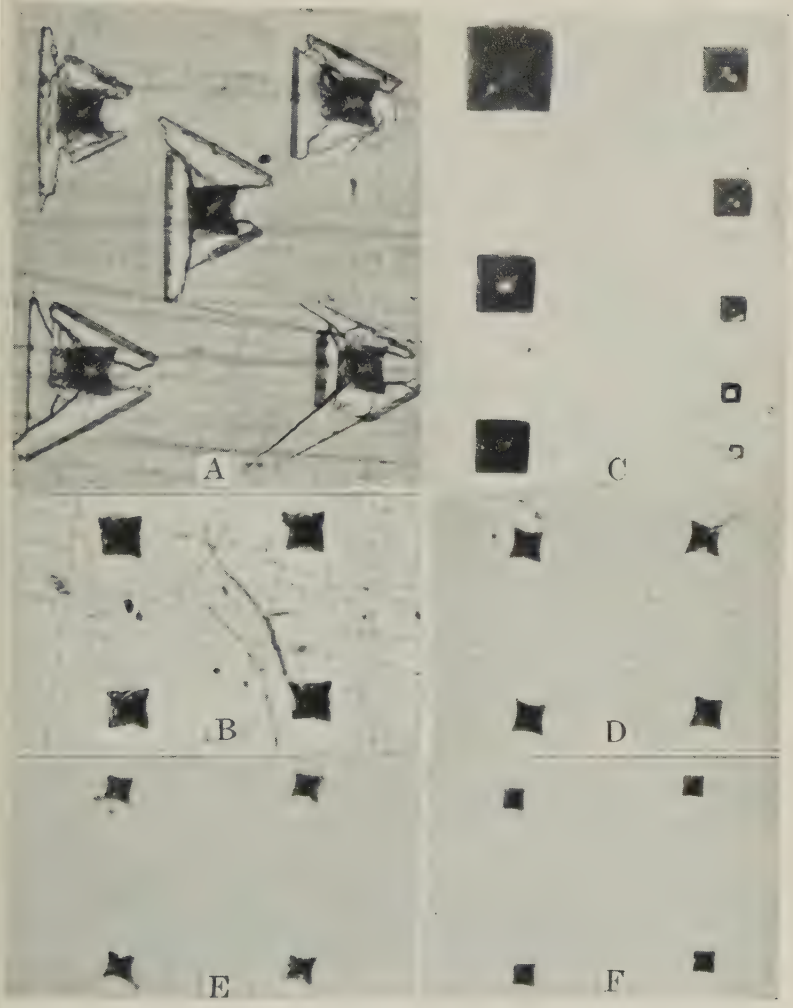


FIG. 1. Hardness of minerals shown by indentations with a diamond point.

A. Calcite, surface normal to optic axis. Load 20g. ×500.
B. Calcite, surface parallel to optic axis. Load 20g. ×500.
C. Fluorite. Loads 100, 70, 50, 40, 30, 20, 10, and 5g. ×500.
D. Quartz, surface normal to optic axis. Load 100g. ×500.
E. Quartz, surface parallel to optic axis. Load 100g. ×500.
F. Corundum, section unknown. Load 100g. ×500.

depend to some extent on the orientation of the crystal under test. Of the minerals tested, the direction of the optical axis was known only in the case of nos. 3 and 7.

The following notes relate to the specimens tested by this means and include samples of silica-glass and synthetic sapphire in addition to Mohs's list of minerals.

1. *Talc.* The impressions were rarely clear to the edges and their size was therefore difficult to determine with accuracy.

2. *Gypsum.* As with no. 1 above, though the impressions were definitely smaller.

3. *Calcite.* When the indentation was made on a face perpendicular to the optic axis, good but somewhat irregular impressions were obtained, surrounded always by cleavage fractures which formed an equilateral triangle (fig. 1 A). When the indentation was on a face parallel with the optic axis good but smaller impressions with slightly concave sides were obtained without any sign of fractures (fig. 1 B). On a cleavage surface the impressions were difficult to measure owing to further fractures.

4. *Fluorite.* The impressions formed on a worked face were perfectly square and regular in outline without any sign of fracture or crumbling, though a tendency for the extreme point of the indenter not to make an impression was noted (fig. 1 C). The impressions made on a cleavage surface were somewhat larger.

5. *Apatite.* The impressions were regular, but apt to flake away shortly afterwards. To avoid this the load was reduced to 20 grams.

6. *Orthoclase.* The impressions were bounded by concave sides or even took the form of a simple cross.

7. *Quartz.* When the indentation was made on a face perpendicular to the optic axis good impressions with concave sides were obtained (fig. 1 D). When the indentation was on a face parallel to the optic axis good but smaller impressions were obtained with markedly concave sides (fig. 1 E). A piece of fused quartz (glass) was also tested and yielded good but larger impressions than the natural crystal.

8. *Topaz.* No trouble due to fractures was experienced on a face ground and polished in our glass shop, but on a second unrelated face, lapped by diamond workers, it was difficult to avoid flaking.

9. *Corundum.* The impressions showed a tendency to be kite-shaped rather than square. This surface was diamond polished (fig. 1 F). A diamond-polished surface of synthetic sapphire gave good, clear impressions.

TABLE I. Comparison of Mohs's scale with Vickers's hardness numbers.

Mohs.	Mineral.	Load grams.	Vickers.
1	Talc	50	47
2	Gypsum, cleavage surface	50	60
3	Calcite, surface ⊥ optic axis ...	50	105
	„ „ ∥ „ „	50	145
	„ cleavage surface	50	136
4	Fluorite	50	200
	„ cleavage surface	50	175
5	Apatite	20	659
6	Orthoclase	50	714
7	Quartz, fused silica-glass	50	480
	„ surface ⊥ optic axis ...	50	1103
	„ „ ∥ „ „ ...	50	1260
8	Topaz	50	1648
9	Corundum	50	2085
	Sapphire (synthetic)	50	2720

It will be seen that the quantitative Vickers's numbers are in the same sequence as Mohs's scale of hardness and that it may now be possible to correlate them, though it must be admitted that the numbers given for the first three minerals in the table are only approximate.

One question still remains unanswered: What is the Vickers's number for diamond? No doubt impressions could be made on at least some faces of diamond, but we have not cared to risk the loss of an expensive diamond point in pursuit of this inquiry.

Eighteenth list of new mineral names.

By L. J. Spencer, C.B.E., M.A., ScD., F.R.S.
Formerly Keeper of Minerals in the British Museum.

[Communicated June 23, 1949.]

PREVIOUS lists of this series have been given every three years at the ends of vols. 11–27 (1897–1946) of this Magazine. Lists 1–17 contained 2537 names and in the present list there are 173. The 1560 names in lists 1–10 are included in one alphabetical arrangement in the General Index (1926) to vols. 11–20 (1895–1925). References to 'Mineralogical Abstracts' are given in the form [M.A. **10**–].

Only a selection of the multitude of compound chemical-cum-mineral names for artificially prepared substitution and base-exchange products has been included. These often have a different meaning from identical names that have been applied to minerals. For example, natural orthoclase containing a small amount of ferric iron replacing alumina has been named ferri-orthoclase or iron-orthoclase (11th List), while the same names have been applied to the artificial compound $KFeSi_3O_8$. In different cases such names have in the first instance been applied either to the natural mineral or to the artificial compound. Further complication has been recently introduced by such terms as copper-chalcanthite and iron-melanterite (q.v.).

Trade-names for partly manufactured mineral products and the host of trivial names for gemstones have in general been excluded. Also misspellings and variants in different languages: e.g. pickingerite for pickeringite; schröckeringite, schröckinergite, and schroeckeringerite for schröckingerite; kleit (q.v.) for clayite.

Every endeavour has been made to trace the author and original spelling of each name. This has, however, not been possible with the many names and variants listed by H. Strunz:[1] a selection has been made here of some of those for which he appears to be responsible.

Achavalite. J. Olsacher, 1939. Bol. Fac. Cienc. Univ. Córdoba, vol. 2, no. 3–4, p. 73 (achavalita). R. Herzenberg, ibid., 1944, vol. 7, no. 4, p. 3 of reprint. Iron selenide FeSe, occurring with other selenides at Cacheuta, Argentina. Named after Prof. Luis Achaval (1870–1938) of Córdoba. [M.A. **10**–8.]

Aldanite. Mentioned by O. M. Shubnikova in a list of uranium minerals, Fersman memorial volume, Acad. Sci. USSR, 1946, p. 79

[1] H. Strunz, Mineralogische Tabellen. Leipzig, 1941. [M.A. **10**–249.]

(Алданит), $k\mathrm{ThO_2}.l\mathrm{UO_2}.m\mathrm{UO_3}.l\mathrm{PbO}$. Presumably from the Aldan region, east Siberia.

Aluminocopiapite. L. G. Berry, 1947. Univ. Toronto Studies, Geol. Ser., no. 51 (for 1946), p. 29. A variety of copiapite in which X in the formula $\mathrm{X(OH)_2Fe'''_4(SO_4)_6}.n\mathrm{H_2O}$ is mainly Al ($\mathrm{Al_2O_3}$ 1·72–4·45 %). Compare Ferricopiapite, 15th List. [M.A. **10**–99.]

Aluminoscorodite. T. Ito and K. Sakurai, 1947. Wada's minerals of Japan, 3rd edit., Tokyo, p. 309 (Aluminoscorodite, Alumskorodit, and Japanese script). A variety of scorodite containing $\mathrm{Al_2O_3}$ 5·11 %, $\mathrm{(Fe,Al)AsO_4.2H_2O}$. The same as aluminum-bearing scorodite [M.A. **9**-142] = aluminous-scorodite [M.A. **9**–262] = aluminian scorodite [M.A. **10**–353] with $\mathrm{Al_2O_3}$ 5·76 % from Oregon. [M.A. **10**–351.]

Ammonium-cryolite. C. Hintze, Handb. Min., 1913, vol. 1, pt. 2, p. 2524 (Ammoniumkryolith). C. Brosset, Arkiv Kemi, Min. Geol., 1946, vol. 21 A, no. 9, p. 8 (ammonium cryolite). Artificial ammonium fluo-aluminate near $\mathrm{(NH_4)_3AlF_6}$, analogous to cryolite, but cubic. See Potassium-cryolite. [M.A. **4**–362, **10**–16, 208.]

Ammonium-mica. J. W. Gruner, 1939. Amer. Min., vol. 24, p. 428 (Ammonium mica). An artificial product containing up to 2·4 % $\mathrm{NH_4}$ obtained by the action of $\mathrm{H_2O_2}$ and $\mathrm{NH_4OH}$ on vermiculite. [M.A. **7**–479.]

Ammonium-syngenite. J. D'Ans, 1906. Ber. Deutsch. Chem. Gesell., vol. 39 (pt. 3), p. 3326 (Ammoniumsyngenit). A. E. Hill and N. S. Yanick, Journ. Amer. Chem. Soc., 1935, vol. 57, p. 650 (Ammonium Syngenite). An artificial compound, $\mathrm{(NH_4)_2SO_4.CaSO_4.2H_2O}$, isomorphous with syngenite. See Koktaite. [M.A. **10**-352.]

Andersonite. J. Axelrod, F. Grimaldi, C. Milton, and K. J. Murata, 1948. Program and Abstracts, Min. Soc. Amer., 29th Annual Meeting, p. 4; Bull. Geol. Soc. Amer., vol. 59, p. 1310; Amer. Min., 1949, vol. 34, p. 274. Hydrous sodium-calcium-uranyl carbonate, $\mathrm{Na_2CaUO_2(CO_3)_3}.n\mathrm{H_2O}$, from Arizona. Named after Charles Alfred Anderson (1902–) of the United States Geological Survey. [M.A. **10**–452.]

Anthoinite. N. Varlamoff, 1947. Ann. (Bull.) Soc. Géol. Belgique, vol. 70, p. B 153. Hydrous aluminium tungstate, $\mathrm{Al_2O_3.2WO_3.3H_2O}$, as white chalky material, from Belgian Congo. Named after Raymond Anthoine, mining geologist of Bruxelles. [M.A. **10**–145, 495.]

Apoanalcite. C. Oftedahl, 1947. Norsk Geol. Tidsskrift, vol. 26, p. 215. H. Neumann, ibid., 1949, vol. 27, p. 171. Hydrated sodium aluminium silicate $\mathrm{NaAl(Al,Si)SiO_6}.1\frac{1}{2}\mathrm{H_2O}$, as red masses in syenite-pegmatite from Nordmarka, Norway; possibly an alteration product of analcime. [M.A. **10**–145, 510.]

Argental. D. R. Hudson, 1943. Metallurgia, Manchester, vol. 29, p. 56. Syn. of moschellandsbergite and landsbergite (17th List), erroneously taking the adjective from 'mercure argental' (L. Cordier, 1802). [M.A. **9**–55.]

Arsenvanadinite. H. Strunz, Min. Tab., 1941, p. 156 (Arsenvanadinit). Syn. of endlichite.

Bacillarite. H. Strunz, Min. Tab., 1941, p. 227 (Bacillarit), given as a synonym of leverrierite, A. Orlov, Tsch. Min. Petr. Mitt., 1942, vol. 54, p. 225 (Bacillarites). An ill-defined clay mineral with bacillary structure, originally described by C. Feistmantel in 1869 as a fossil 'Bacillarites problematicus'. [M.A. **10**–24, 29.]

Barium-aragonite. H. Strunz, Tab. Min., 1941, p. 118 (Barium-aragonit). Syn. of alstonite.

Baryt-hedyphane. G. Lindström, Geol. För. Förh. Stockholm, 1879, vol. 4, p. 266 (Barythaltig hedyfan från Långban); British Museum, Index of minerals, 9th edit., 1881 (Barythedyphane), from a dealer's label; ibid., 27th edit., 1936 (Baryt-hedyphane). Variety of hedyphane containing BaO 8·03 %. Later named calcium-barium-mimetite (q.v.).

Barytoanglesite. P. Ramdohr, 1947. Abhandl. Deutsch. Akad. Wiss. Berlin, for 1945–6, no. 4, p. 22 (Barytoanglesit). Variety of anglesite containing some barium. [M.A. **10**–253.]

Basaluminite. F. A. Bannister and S. E. Hollingworth, 1948. Nature, London, vol. 162, p. 565. Hydrous basic aluminium sulphate, $2Al_2O_3.SO_3.10H_2O$, as white compact material lining crevices in iron-stone from Irchester, Northamptonshire. Felsőbányite with the same formula has a different X-ray pattern. So named because more basic than aluminite. See Hydro-basaluminite. [M.A. **10**–452.]

Bayleyite. J. Axelrod, F. Grimaldi, C. Milton, and K. J. Murata, 1948. Program and Abstracts, Min. Soc. Amer., 29th Annual Meeting, p. 4; Bull. Geol. Soc. Amer., vol. 59, p. 1310; Amer. Min., 1949, vol. 34, p. 274. Hydrous magnesium-uranyl carbonate, $Mg_2UO_2(CO_3)_3.nH_2O$, from Arizona. Named after William Shirley Bayley (1861–1943) of the University of Illinois. [M.A. **10**–452.]

Beryllium-felspar. M. E. Kazakova, 1946. Compt. Rend. (Doklady) Acad. Sci. URSS, vol. 54, p. 623 (beryllium feldspar). E. I. Kutukova, ibid., p. 724 (beryllium microcline). Felspar containing BeO 1·2 %, with bavenite from the decomposition of beryl and plagioclase in the emerald mines, Urals. [M.A. **10**–247.]

Billietite. J. F. Vaes, 1947. Ann. (Bull.) Soc. Géol. Belgique, vol. 70, p. B 214. Hydrous barium uranate as amber-yellow orthorhombic

plates resembling becquerelite, from Katanga. Named in memory of Valère Louis Billiet (1903-1945) of Ghent. [M.A. **10**–146, 255.]

Boryslawite. British Museum Index of minerals, 18th edit., 1895 (Boryslavite), from a dealer's label (1890). C. Hintze, Handb. Min., 1933, vol. 1, Abt. 4, pt. 2, p. 1362 (Boryslawit). A hard brittle variety of ozocerite from Borysław, Galicia.

Bowleyite. H. P. Rowledge and J. D. Hayton, 1948. Journ. Roy. Soc. W. Australia, vol. 33 (for 1946–7), p. 45. Hydrous silicate of Al, Ca, Be (BeO 7·30 %), $3(Ca,Be)O.2Al_2O_3.3SiO_2.2H_2O+n(Li,Na)_2O$, as white compact material with beryl in pegmatite, from Londonderry, Western Australia. Named after H. Bowley, late government Chemist and Mineralogist of Western Australia. [M.A. **10**–508.]

Bredigite. C. E. Tilley and H. C. G. Vincent, 1948. Min. Mag., vol. 28, p. 255. Calcium orthosilicate, Ca_2SiO_4, orthorhombic high-temperature α'-form, in the dolerite-chalk contact-zone at Scawt Hill, Co. Antrim, and in the gabbro-limestone contact-zone on the island of Muck, Inverness-shire. Named after Max Albert Bredig (1902–), of New York, formerly of Berlin.

Bromcarnallite. A. de Schulten, 1897. Bull. Soc. Chim. Paris, ser. 3, vol. 17, p. 166 (Carnallites bromées). K. R. Andress and O. Saffe, Zeits. Krist., 1939, vol. 101, p. 451 (Bromkarnallit). Artificial mixed crystals $KMg(Cl,Br)_3.6H_2O$. Carnallite from New Mexico, Utah, and Spain contains Br 0·1–0·29 %. [M.A. **7**–490; **10**–304, 344.]

Bromchlorargyrite. H. Strunz, Min. Tab., 1941, p. 85 (Bromchlorargyrit). Syn. of embolite.

Buetschliite. C. Milton and J. M. Axelrod, 1946. Bull. Geol. Soc. Amer., vol. 57, p. 1218; Amer. Min., 1947, vol. 32, pp. 204, 607. Hydrous potassium and calcium carbonate, $3K_2CO_3.2CaCO_3.6H_2O$, probably hexagonal, formed by the hydration of fairchildite (q.v.) in the fused wood-ash of burnt trees. Named after Johann Adam Otto Bütschli (1848–1920), formerly professor of zoology at Heidelberg, who prepared the compound artificially. [Not the bütschliite of R. Lang, 1914; 7th List.] [M.A. **10**–101, 252.]

Cadmiumspat. H. Strunz, Min. Tab., 1941, p. 117. Syn. of otavite (4th List; M.A. **8**–366.)

Calciobaryt. H. Strunz, Min. Tab., 1941, p. 130. Syn. of calcareobarite (T. Thomson, 1836).

Calcium-barium-mimetite. H. Strunz, Min. Tab., 1941, p. 156 (Calciumbariummimetesit). Syn. of baryt-hedyphane (q.v.).

Calcium-pectolite. E. S. Larsen, 1917. Amer. Journ. Sci., ser. 4, vol. 43, p. 465 (calcium pectolite). R. Koechlin, Min. Taschenb. Wien.

Min. Gesell., 2nd edit., 1928, p. 15 (Calciumpektolith). Syn. of eakleite = xonotlite. [M.A. **1**–206; **2**–253.]

Calcium-pyromorphite. H. Strunz, Min. Tab., 1941, p. 156 (Calciumpyromorphit). Syn. of polysphaerite.

Calcium-strontianite. H. Strunz, Min. Tab., 1941, p. 118 (Calciumstrontanit). The same as calciostrontianite (A. Cathrein, 1888), syn. of emmonite (T. Thomson, 1836).

Calclacite. R. Van Tassel, 1945. Bull. Musée Roy. Hist. Nat. Belgique, vol. 21, no. 26, p. 2. Hydrous chloride and acetate of calcium, $CaCl_2.Ca(C_2H_3O_2)_2.10H_2O$, formed as a fibrous efflorescence on certain limestones stored in wooden drawers. Named from the composition Ca,Cl,Ac. [M.A. **10**–101.]

Calcowulfenite. V. Zepharovich, 1884. Zeits. Kryst. Min., vol. 8, p. 583 (Kalkhaltige Wulfenit). A. Krantz's label, 1884 (Kalkwulfenit). Student's index to the collection of minerals, British Museum, 13th edit. 1886 (Calco-wulfenite); ibid., 27th edit., 1936 (Calcowulfenite). A variety of wulfenite containing CaO 1·24 %, from Carinthia.

Cerium-ankerite. H. Strunz, Min. Tab., 1941, p. 118 (Ceriumankerit, Coddazit [sic]). Syn. of codazzite (11th List).

Cerorthite. A variety of orthite rich in cerium (Ce_2O_3 20 %) from Finland. Bull. Soc. Franç. Min., 1933, vol. 56, p. 188. Student's index to the collection of minerals, British Museum, 27th edit., 1936 (Cerorthite), from a dealer's label (Cer-Orthit).

Chernyshevite. English equivalent of tschernichewite (4th List). Named after T. H. Чернышевъ (1856–1914).

Chrome-antigorite. H. Strunz, Min. Tab., 1941, p. 204 (Chrom-Antigorit). Antigorite containing some chromium.

Chrome-magnetite. J. J. Frankel, 1942. South African Journ. Sci., vol. 38, p. 153. A magnetic mineral containing Cr_2O_3 12·34 %, associated with non-magnetic chromite and titaniferous magnetite at Lydenburg, Transvaal. Compare iskulite (16th List). [M.A. **10**–493.]

Chrome-phengite. P. de Wijkerslooth, 1943. Maden Tetkik ve Arama Enstitüsü Mecmuası, Ankara, vol. 8, p. 256 (kromfengit, Turkish), p. 261 (Chromphengit, German). A chromium-bearing mica enclosed in chromite ore. [M.A. **9**–244.]

Chrome-tourmaline. A. Cossa and A. Arzruni, 1883, Zeits. Kryst. Min., vol. 7, p. 1 (Chromturmalin). A. G. Gill, Johns Hopkins Circulars, 1889, vol. 8, p. 101 (chrome-tourmaline). Variety of tourmaline from Urals (Cr_2O_3 10·86 %) and Maryland (Cr_2O_3 4·32 %).

Cleïte. S. J. Thugutt, 1945. Arch. Min. Tow. Nauk. Warszaw. (Arch. Min. Soc. Sci. Varsovie), vol. 15 (for 1939–45), p. 233 (cleïte, French), p. 236 (kleit, Polish). Variants of clayite (5th List). [M.A. **10**–23.]

Cobalt-manganese-spar. C. Bergemann, 1857. Verh. Naturhist. Ver. Rheinl. Westph., vol. 14, p. 111 (Kobalt-Manganspath). British Museum Catalogue of minerals, 1st edit., 1863 (Cobalt manganese spar). Rhodochrosite from Rheinbreitbach containing $CoCO_3$ 3·71 %.

Cobaltorhodochrosite. Bull. Soc. Franç. Min., 1936, vol. 59, p. 385. Cobaltiferous rhodochrosite from Schneeberg, Saxony. The same as cobalt-manganese-spar (q.v.).

Copper-chalcanthite. A. N. Winchell, 1942. Elements of mineralogy, p. 292; Amer. Min., 1949, vol. 34, p. 223 (Copper chalcanthite). Syn. of chalcanthite ($CuSO_4.5H_2O$), which with siderotil ($FeSO_4.5H_2O$) and cobalt-chalcanthite = bieberite ($CoSO_4.5H_2O$) is classed as subspecies under a species 'chalcanthite'. [M.A. **10**–568.]

Courzite. S. J. Thugutt, 1945. See Kurtzite.

Csiklovaite. S. Koch, 1948. Acta Min. Petr., Publ. Min. Petr. Inst. Univ. Szeged, vol. 2, p. 11 (csiklovait), p. 19 (csiklovaite). Sulphide and telluride of bismuth Bi_2TeS_2, in the series $Bi_2Te_3 \rightarrow Bi_2Te_2S \rightarrow Bi_2TeS_2 > Bi_2S_3$; isomorphous with the associated tetradymite (Bi_2Te_2S), but differing in colour and etching reactions. Named from the locality Csiklova (Ciclova), Banat, Romania. [M.A. **10**–446, 509.]

Cuproarquerite. R. Koechlin, Min. Taschenb. Wien. Min. Gesell., 2nd edit., 1928, p. 19 (Cuproarquerit). Silver-amalgam containing some copper, from Chile.

Cymrite. W. C. Smith, F. A. Bannister, and M. H. Hey, 1949. Min. Mag., vol. 28, p. 676. Barium aluminium silicate, $BaAlSi_3O_8(OH)$, as hexagonal crystals from the Benallt manganese mine, Wales. Named from Cymru, the Welsh name for Wales.

Dervillite. R. Weil, 1941. Rev. Sci. Nat. Auvergne, Clermont-Ferrand, vol. 7, p. 110. An incompletely determined black metallic mineral containing Sb, Pb, (Bi?), S, as minute monoclinic crystals from Markirch, Alsace. Named after Dr. Henri Derville of Strasbourg university. [M.A. **10**–353.]

Diderichite. J. V. Vaes, 1947. Ann. (Bull.) Soc. Géol. Belgique, vol. 70, p. B 224. Slightly hydrated uranium carbonate as yellow-green fibrous crusts, orthorhombic, from Katanga. Named after Nobert Diderich, who was the first to study the copper and iron ores of Katanga. [M.A. **10**–146.]

Dunhamite. E. E. Fairbanks, 1946. Econ. Geol., vol. 41, p. 767. A pale brown alteration product, perhaps $PbO.TeO_2$, of altaite from Organ Mts., New Mexico. Named after Dr. Kingsley Charles Dunham (1910–) of the Geological Survey of Great Britain, who first noticed it (Bull. New Mexico School of Mines, 1935, no. 11, p. 158). See microdunhamite. [M.A. **10**–100.]

Duplexite. H. P. Rowledge and J. D. Hayton, 1948. Journ. Roy. Soc. W. Australia, vol. 33 (for 1946–47), p. 49. Hydrous silicate, $6CaO.4BeO.Al_2O_3.14SiO_2.2H_2O$. as white rosettes with beryl in pegmatite from Londonderry, Western Australia. Differing from bavenite in containing rather more BeO (7 %). Named after S. Duplex, manager of the felspar quarry, who found the material. [M.A. **10**–508.]

Epiianthinite. A. Schoep and S. Stradiot, 1947. Amer. Min., vol. 32, p. 344. Uranic hydroxide, $yUO_3.xH_2O$, as yellow orthorhombic crystals, an alteration product of ianthinite (11th List); from Belgian Congo. [M.A. **10**–145.]

Eulite. A. Poldervaart, 1947. Min. Mag., vol. 28, p. 165. F. Walker and A. Poldervaart, Bull. Geol. Soc. Amer., 1949, vol. 80, p. 632. Orthopyroxenes containing 70–90 mol. % $FeSiO_3$. A contraction of eulysite (*εὔλυτος*, easy to dissolve or break), a rock in which the mineral occurs.

Fairchildite. C. Milton and J. M. Axelrod, 1946. Bull. Geol. Soc. Amer., vol. 57, p. 1218; Amer. Min., 1947, vol. 32, pp. 204, 607. Potassium and calcium carbonate, $K_2CO_3.CaCO_3$, hexagonal, formed by the fusion of wood-ash in burnt trees. On hydration it yields buetschliite (q.v.) and calcite. Named after John Gifford Fairchild (1882–) of the United States Geological Survey. [M.A. **10**–101, 252.]

Falkenstenite. T. F. W. Barth, 1945. Skrifter Norske Videnskaps-Akad. Oslo, I. Mat.-Naturv. Kl., 1945, no. 8, p. 13. An incompletely determined tetragonal zeolite, related to ashcroftine and gonnardite, forming the groundmass (40 %) of variolite at Falkensten, Oslo fjord. Named from the locality. [M.A. **10**–5.]

Ferrialunogen. H. Strunz, Min. Tab., 1941, p. 135 (Ferrialunogen), p. 239 (Ferroalunogen). Alunogen with some alumina replaced by ferric oxide. Identified with tecticite (Tekticit).

Ferribraunite. B. Wasserstein, 1943. Econ. Geol., vol. 38, p. 393. Intermediate between braunite and sitaparite. [M.A. **9**–38.]

Ferriedenite. A. N. Winchell, 1949. Amer. Min., vol. 34, p. 225. Hypothetical molecule $NaCa_2Fe_3Fe_2O_2Si_7AlO_{22}$ in hornblendes, differing from ferroedenite (q.v.) in containing some ferric iron. [M.A. **10**–568.]

Ferrihastingsite. A. N. Winchell, 1949. Amer. Min., vol. 34, p. 225. Hypothetical molecule $NaCa_2Fe_2(Al,Fe)_3O_2Si_6Al_2O_{22}$, differing from ferrohastingsite (12th List) in containing some ferric iron. [M.A. **10**-568.]

Ferrimontmorillonite. I. Z. Korin, 1939. Bull. Acad. Sci. URSS, Sér. Géol., 1939, no. 6, p. 149 Ферримонтмориллонит), p. 158 (ferrimontmorillonite). V. P. Ivanova, D. S. Belyankin Jubilee vol., Acad. Sci. USSR, 1946, p. 102. The correct form of ferromontmorillonite (15th List). $Fe_2O_3.4SiO_2.2H_2O$. Syn. of nontronite. [M.A. **9**-240, **10**-554.]

Ferroactinolite. N. Sundius, 1946. Årsbok Sveriges Geol. Undersök., vol. 40, p. 7. A hypothetical molecule $Ca_2Fe''_5Si_8O_{22}(OH)_2$ to explain the composition of the amphibole group. [M.A. **10**-70.]

Ferroedenite. N. Sundius, 1946. Årsbok Sveriges Geol. Undersök., vol. 40. p. 6. A hypothetical molecule $NaCa_2Fe''_5AlSi_7O_{22}(OH)_2$ to explain the composition of the amphibole group. [M.A. **10**-70.]

Ferrohedenbergite. A. Poldervaart, 1947. Min. Mag., vol. 28, pp. 159, 161. F. Walker and A. Poldervaart, Bull. Geol. Soc. Amer., 1949, vol. 80, p. 632. A variety of hedenbergite richer in iron.

Ferromagnesite. H. Strunz, Min. Tab., 1941, p. 117 (Ferromagnesit). Syn. of mesitite. Similarly, for other mixed crystals of the calcite group: Zinkocalcit, Kobaltcalcit, Mangancalcit, Strontiumcalcit, Bariumcalcit, Zinkrhodochrosit, Ferrorhodochrosit, Kalkrhodochrosit, Zinksiderit, Mangansiderit, Calciumsiderit, Ferrosmithsonit, Mangansmithsonit.

Ferromangandolomite. J. A. Smythe and K. C. Dunham, 1947. Min. Mag., vol. 28, p. 65. Hypothetical molecule $(Fe,Mn)CO_3.CaCO_3$ as an end-member of the ankerite series.

Ferro-ortho-titanate. F. Mogensen, 1946. See Ulvöspinel.

Ferrophengite. A. N. Winchell, 1949. Amer. Min., vol. 34, p. 223. A hypothetical molecule $K_2FeAl_3(OH)_4Si_7AlO_{20}$, classed as a subspecies of muscovite. Compare picrophengite (q.v.). [M.A. **10**-568.]

Ferrorichterite. N. Sundius, 1946. Årsbok Sveriges Geol. Undersök., vol. 40, p. 16. A hypothetical molecule $Na_2CaFe''_5Si_8O_{22}(OH)_2$ to explain the composition of the amphibole group. [M.A. **10**-70.]

Fersmite. E. M. Bohnstedt-Kupletskaya and T. A. Burova, 1946. Compt. Rend. (Doklady) Acad. Sci. URSS, vol. 52, p. 69. Calcium niobate, $CaNb_2O_5$, with some other constituents, as black orthorhombic crystals resembling columbite and euxenite, from the Urals. Named after

Aleksandr Evgenievich Fersman, Александр Евгеньевич Ферсман (1883–1945). Not to be confused with fersmanite (12th List). [M.A. **10**–102.]

Fluor-chondrodite. K. Rankama, 1947. Amer. Min., vol. 32, p. 154. Artificially prepared chondrodite, $MgF_2.2Mg_2SiO_4$, with OH completely replaced by F. [M.A. **10**–106.]

Fluor-norbergite. K. Rankama, 1947. Amer. Min., vol. 32, p. 154. Artificially prepared norbergite, $MgF_2.Mg_2SiO_4$, with OH completely replaced by F. [M.A. **10**–106.]

Frohbergite. R. M. Thompson, 1946. Bull. Geol. Soc. Amer., vol. 57, p. 1238; Univ. Toronto Studies, Geol. Ser., 1947, no. 51 (for 1946), p. 35; Amer. Min., 1947, vol. 32, p. 210. Iron telluride, $FeTe_2$, isomorphous with marcasite, found in polished sections of telluride ore from Montbray, Quebec. Named after Dr. Max Hans Frohberg, mining geologist, of Toronto. [M.A. **10**–99.]

Giannettite. D. Guimarães, 1948. Bol. Inst. Tecn. Indust. Minas Gerais, no. 6, p. 22 (giannettita), p. 62 (giannettite). Chloro-zirconotitano-silicate of Ca, Na, Mn, as minute triclinic crystals with aegirine in nepheline-rocks from Poços de Caldas, Brazil. Named after Dr. Americo René Giannetti, mining engineer. [M.A. **10**–510.]

Harbolite. C. E. Taşman, 1946. Maden Tetkik ve Arama Enstitüsü Mecmuası, Ankara, vol. 11, p. 50 (harbolit), p. 51 (harbolite); Bull. Amer. Assoc. Petroleum Geol., 1946, vol. 30, p. 1051. A hard lustrous asphalt from Harbol, SE. Turkey. Named from the locality. [M.A. **10**–7, 354.]

Harkerite. C. E. Tilley, 1948. Geol. Mag. Hertford, vol. 85, p. 215; Min. Mag., 1949, vol. 28, p. lxxi. Carbonate-borosilicate of calcium and magnesium in dolomite skarns from Skye. Named after Alfred Harker (1859–1939) of Cambridge. [M.A. **10**–355.]

Heikkolite. [Y. Kinosaki, 1935. Trans. Mining. Eng. Assoc., vol. 18, no. 3 (Japanese). Minerals of Korea, 2nd edit., Bull. Geol. Surv. Chosen, 1941, no. 15, p. 198. J. Harada, Journ. Geol. Soc. Japan, 1939, vol. 46, p. 290; S. Hori, ibid., 1942, vol. 49, p. 445.] An alkali-amphibole with no extinction between crossed nicols and other optical anomalies. Named from the locality, Heiko, Kogen-do, Korea. Not to be confused with hokutolite (6th List).

Hydro-basaluminite. F. A. Bannister and S. E. Hollingworth, 1948. Nature, London, vol. 162, p. 565. Hydrous basic aluminium sulphate as a white plastic material occurring with basaluminite (q.v.) and differing from this in its X-ray pattern. When air dried it loses

about 50 % H_2O, falling to a white powder of basaluminite. [M.A. **10**–452.]

Hydrohausmannite. W. Feitknecht and W. Marti, 1945. Helvetica Chim. Acta, vol. 28, p. 133 (Hydrohausmannit). An artificial product obtained, together with hausmannite, by the oxidation of $Mn(OH)_2$. It has the composition $MnO_{1\cdot15}$—$MnO_{1\cdot45}+\frac{1}{2}H_2O$ and gives an X-ray pattern similar to that of hausmannite (Mn_3O_4). Not the hydrohausmannite of A. K. Boldyrev, 1928 (14th List). [M.A. **10**–105.]

Hydroxyl-sodalite. W. Borchert and J. Keidel, 1947. Heidelberg. Beitr. Min. Petr., vol. 1, p. 3 (Hydroxyd-Sodalith, Hydroxydsodalith). An artificial product $Na_8Al_6Si_6O_{24}(OH)_2$.aq. with the crystal-structure of sodalite (Chloridsodalith). [M.A. **10**–364.]

Iron-melanterite. A. N. Winchell, 1942. Elements of mineralogy, p. 291; Amer. Min., 1949, vol. 34, p. 223 (Iron Melanterite). Syn. of melanterite ($FeSO_4.7H_2O$), classed with boothite ($CuSO_4.7H_2O$) and zinc-copper melanterite ($(Zn,Cu,Fe)SO_4.7H_2O$) as sub-species under a species 'melanterite'. [M.A. **10**–568.]

Johachidolite. E. Iwase and N. Saito, 1942. [Sci. Papers Inst. Phys. Chem. Research, Tokyo, vol. 39, p. 300.] Abstr. in Amer. Min., 1948, vol. 33, p. 98. Hydrous fluoborate, '$H_6Na_2Ca_3Al_4F_5B_6O_{20}$', colourless, optically biaxial. In nepheline veins from Johachido, Korea. Named from the locality. [M.A. **10**–253.]

Jujuyite. F. Ahlfeld, 1948. Econ. Geol., vol. 43, p. 600. Iron antimonate, as brown to black compact masses intermixed with opal, from prov. Jujuy, Argentina. Named from the locality. [M.A. **10**–508.]

Kleit. Polish form of clayite. See Cleïte.

Koktaite. J. Sekanina, 1948. Acta Acad. Sci. Nat. Moravo-Silesicae, vol. 20, no. 1 (koktait, koktaite, ammonium-syngenite). Hydrated sulphate of calcium and ammonium, $(NH_4)_2Ca(SO_4)_2.H_2O$, as acicular monoclinic crystals pseudomorphous after gypsum, from Moravia. Named after Dr. Jaroslav Kokta of Brno, Moravia. See Ammonium-syngenite. [M.A. **10**–352.]

Korteite. [C. Prager, 1923?]. Student's index to the collection of minerals, British Museum, 27th edit., 1936, p. 21, from a dealer's label. Described as $MgO.Al(OH)_3$, found with wathlingenite (q.v.). Named after G. Korte, director of potash-salt works. Identical with koenenite (3rd List).

Kurtzite. S. J. Thugutt, 1945. Arch. Min. Tow. Nauk. Warszaw. (Arch. Min. Soc. Sci. Varsovie), vol. 15 (for 1939–45), p. 182 (courzite), p. 187 (kurcyt). A zeolite from the Crimea, identified by A. E. Fersman

(1909) as wellsite, is given a complex structural formula different from that of wellsite. Named from the locality, Kurtzy (Курцы) village near Simferopol. [M.A. **10**–6.]

Kuttenbergit. R. Koechlin, Min. Taschenb. Wien. Min. Gesell., 2nd edit., 1928, p. 36. Another form of kutnohorite (4th List), named from the locality in Bohemia: Kutná Hora in Czech, Kuttenberg in German.

Lembergite. T. Sudo, 1943. [Bull. Chem. Soc. Japan, vol. 18, p.—]; abstract in Amer. Min., 1947, vol. 32, p. 483. Hydrous silicate of Al, Fe, Mg, Ca, belonging to the montmorillonite group, as a fine-grained green cement in ferruginous sandstones from Japan. Named after Johann Theodor Lemberg (1842–1903) of Dorpat, who described similar material in 1877. Not the lembergite of A. Lagorio, 1895 (1st List). [M.A. **10**–147.]

Lime-bronzite. A. Poldervaart, 1947. Min. Mag, vol. 28, p. 170. An unstable form of bronzite containing $CaSiO_3$ up to 9 %.

Llallagualite. M. C. Bandy, 1946. Mineralogía de Llallagua, Bolivia, La Paz, p. 56 (Llallagualita, Monasita romboédrica). Provisional name for an undescribed rhombohedral mineral which has perhaps the same composition as monazite. Named from the locality Llallagua (pronounced Yayawa). [M.A. **10**–9.]

Loughlinite. J. J. Fahey and J. M. Axelrod, 1947. Program and Abstracts, 28th Annual Meeting, Min. Soc. Amer., p. 9; Bull. Geol. Soc. Amer., vol. 58, p. 1178; Amer. Min., 1948, vol. 33, p. 195 (abstract). Hydrous magnesium silicate, $MgSi_2O_5.aq.$, an asbestiform mineral from Wyoming. Named after Dr. Gerald Francis Loughlin (1880–1946) formerly of the United States Geological Survey. [M.A. **10**–255.]

Magnesium-cordierite. H. M. Richardson and G. R. Rigby, 1949. Min. Mag., vol. 28, p. 548. Synonym of cordierite, distinguishing it from iron-cordierite (10th List) and manganese-cordierite (q.v.).

Magnesium-phosphoruranite. H. Strunz, Min. Tab., 1941, p. 165, (Magnesiumphosphoruranit). Syn. of saleite (13th List). Similarly, Kupferphosphoruranit (torbernite), Kupferarsenuranit (zeunerite), Calciumphosphoruranit (autunite), Calciumarsenuranit (uranospinite), Bariumphosphoruranit (uranocircite).

Magnesium-wollastonite. C. E. Tilley, 1948. Amer. Min., vol. 33, p. 737 (magnesium wollastonite solid solutions). Compare iron-wollastonite (14th List).

Manganese-anorthite. O. Glaser, 1926. Centralblatt Min., Abt. A, p. 86 (Mangananorthit). R. B. Snow, Journ. Amer. Ceramic Soc., 1943, vol. 26, p. 19 (manganese anorthite); J. R. Rait and H. W. Pinder,

Journ. Iron & Steel Inst., 1947, vol. 154 (no. 2 for 1946), p. 375 P (manganese felspar, manganese anorthite). Artificial $MnAl_2Si_2O_8$, analogous to anorthite, in the system MnO–Al_2O_3–SiO_2. [M.A. **10**–462.]

Manganese-cordierite. R. B. Snow, 1943. Journ. Amer. Ceramic Soc., vol. 26, p. 15 (manganese compound analogous to cordierite). H. M. Richardson and G. R. Rigby, Min. Mag., 1949, vol. 28, p. 551 (Manganese-cordierite). Artificial $2MnO.2Al_2O_3.5SiO_2$ in the system MnO–Al_2O_3–SiO_2. [M.A. **10**–462.]

Manganese-gehlenite. O. Glaser, 1926. Centralblatt. Min., Abt. A, p. 86 (Mangangehlenit). Artificial $2MnO.Al_2O_3.SiO_2$, analogous to gehlenite, in the system MnO–Al_2O_3–SiO_2.

Manganmelanterit. H. Strunz, Min. Tab., 1941, p. 134. $(Fe,Mn)SO_4.7H_2O$. Syn. of Luckyit = luckite.

Mangan-niobite. H. Strunz, Min. Tab., 1941, p. 106 (Manganniobit). Syn. of manganocolumbite.

Manganonatrolite. C. A. Thomas, 1947. Rocks and Minerals, Peekskill, N.Y. vol. 22, p. 804. Variety of natrolite from Pennsylvania. [M.A. **10**-294.]

Mangan-orthite. L. N. Ovchinnikov and N. N. Tzimbalenko, 1948. Doklady Acad. Sci. USSR, vol. 63, p. 191 (манган-ортит). A variety of orthite containing MnO 5·37 %, from Vishnevy Mt., Urals. [M.A. **10**-453.]

Manganoxyapatite. H. Strunz, Min. Tab., 1941, p. 156 (Manganoxyapatit). Syn. of manganvoelckerite (15th List).

Masuyite. J. F. Vaes, 1947. Ann. (Bull.). Soc. Géol. Belgique, vol. 70, p. B 219. Hydrous lead uranate as orange-red orthorhombic scales, from Katanga. Named in memory of Gustave Masuy who died a prisoner of war in 1945. [M.A. **10**–146.]

Mavinite. B. Rama Rao, 1946. Rec. Mysore Geol. Dept., vol. 43 (for 1944), p. 27. A dark-green brittle mica, $3(Fe,Mg)O.6(Al,Fe)_2O_3.7SiO_2.9H_2O$, intermediate between chloritoid and xanthophyllite. Named from the locality, Mavinhalli, Mysore. [M.A. **10**–7.]

Mechernichite. G. Kalb, not published, later replaced by bravoite [M.A. **3**-154.] Dealer's label (1925) in British Museum. H. Strunz, Min. Tab., 1941, p. 256; P. Ramdohr, Klockmann's Lehrb. Min., 13th edit., 1948, pp. 376, 656 (Mechernichit). Named from the locality, Mechernich, Eifel, Rhineland. Syn. of bravoite. [M.A. **3**–154, 339; Min. Mag. **25**–609.]

Merumite. S. Bracewell, 1946. Geology and mineral resources, section 4 in Handbook of natural resources of British Guiana, George-

town, 1946, p. 36. Hydrous chromic oxide (Cr_2O_3 81·30, Al_2O_3 6·55, H_2O 8·18 %, &c.), from the Merume river, Mazaruni district. Named from the locality. [M.A. **10**–292.]

Micro-dunhamite. E. E. Fairbanks, 1947. Amer. Min., vol. 32, p. 683. Synonym of dunhamite (q.v.). The prefix 'micro' to indicate that the determination was made only in polished sections under the microscope. [M.A. **10**–255.]

Miskeyite. Trade-name for a compact chlorite (pseudophite) used as an ornamental stone from St. Gallenkirch, Vorarlberg. Named after J. von Miskey, director of the Miskeyitwerksgesellschaft. F. Berwerth, Tschermak's Min. Petr. Mitt., 1912, vol. 31, p. 112. W. C. Smith, Min. Mag., 1912, vol. 31, p. 112.

Molybdoscheelite. H. Strunz, Min. Tab. 1941, p. 144 (Molybdoscheelite, *pl.*), p. 258 (Molybdoscheelit). O. H. Ödman, Årsbok Sveriges Geol. Undersök., 1947, vol. 41, no. 6, p. 47 (molybdo-scheelite). Calcium tungstate and molybdate, $Ca(W,Mo)O_4$, as mixed crystals intermediate between scheelite and powellite. Syn. of seyrigite (15th List). [M.A. **10**–492.]

Monteponite. E. E. Fairbanks, 1946. Econ. Geol., vol. 41, p. 767. Cadmium oxide, CdO, as minute black octahedra described by B. Neumann and E. Wittich (Natürliches Cadmiumoxyd, Chem.-Ztg., 1901, vol. 25, p. 561; E. Wittich and B. Neumann, Cbl. Min., 1901, p. 549) from Monteponi, Sardinia. Named from the locality. [M.A. **10**–100.]

Natronbiotite. H. Strunz. Min. Tab., 1941, p. 199 (Natronbiotit). Biotite with potassium partly replaced by sodium.

Nickel-asbolane. S. Dimitrov, 1942. Ann. Univ. Sofia, Fac. Phys.-Mat., Sci. Nat., vol. 38, p. 207 (никеловъ асболанъ, Bulgarian), p. 225 (Nickel-Asbolan, German). A variety of asbolane containing NiO 3·58 %, from Bulgaria. [M.A. **10**–300.]

Nickel-pyrite. H. Strunz, Min. Tab., 1941, p. 80; P. Ramdohr, Klockmann's Lehrb. Min., 13th edit., 1948, p. 376 (Nickelpyrit). Syn. of bravoite.

Nigerite. R. Jacobson and J. S. Webb, 1947. Min. Mag., vol. 28, p. 118. F. A. Bannister, M. H. Hey, and H. P. Stadler, ibid., p. 129. Aluminate of tin (SnO_2 25·33 %), iron, zinc, &c. $(Zn,Mg,Fe'')(Sn,Zn)_2(Al,Fe''')_{12}O_{22}(OH)_2$, as dark brown hexagonal plates from Nigeria. Named from the country. [M.A. **10**–276.]

Nitrokalite. H. Strunz, Min. Tab., 1941, p. 115 (Nitrokalit, Kalisalpeter). Syn. of nitre, KNO_3.

Nitronatrite. E. F. Glocker, 1847. Generum et specierum mineralium . . . synopsis, p. 292 (Nitronatrites, Nitronatrit). Syn. of nitratine, soda-nitre, $NaNO_3$.

Nuevite. J. Murdoch, 1946. Bull. Geol. Soc. Amer., vol. 57, p. 1219; Amer. Min., 1947, vol. 32, p. 204. Titano-niobate of yttrium and iron as black grains and orthorhombic (?) crystals in quartz from Nuevo, Riverside Co., California. Named from the locality. [M.A. **10**–100.]

Paragearksutite. N. A. Smolyaninov and E. N. Isakov, 1946. D. S. Belyankin Jubilee vol., Acad. Sci. U.S.S.R., p. 147 (парагеаркситит), Hydrous calcium aluminium fluoride $4CaF_2.4Al(F,OH)_3.3H_2O$, differing from gearksutite in containing slightly less water, from Transbaikalia. [M.A. **10**–453.]

Paraguanajuatite. P. Ramdohr, 1948. Klockmann's Lehrb. Min., 13th edit., p. 360. Rhombohedral paramorphs after natural and artificial orthorhombic guanajuatite, $Bi_2(Se,S)_3$.

Parajamesonite. V. Zsivny and I. v. Náray-Szabó, 1947. Schweiz. Min. Petr. Mitt., vol. 27, p. 183 (Parajamesonit). Dimorphous with jamesonite, $4PbS.FeS.3Sb_2S_3$, distinguished by the X-ray pattern. [M.A. **10**–254.]

Para-Kupferglanz. H. Strunz, Min. Tab., 1941, p. 65. Paramorphs of low-temperature orthorhombic Cu_2S after high-temperature cubic [hexagonal?] α-Cu_2S. Syn. of chalcosine. [M.A. **2**–506, **10**–202.]

Paraschoepite. A. Schoep and S. Stradiot, 1947. Amer. Min., vol. 32, p. 344. Uranic hydroxide, $5UO_3.9\frac{1}{2}H_2O$, as yellow orthorhombic crystals, differing from schoepite (10th List) in its optical properties; from Katanga. [M.A. **10**–145, 544.]

Para-Silberglanz. H. Strunz, Min. Tab., 1941, p. 66. Paramorphs of low-temperature orthorhombic Ag_2S (acanthite) after high-temperature cubic α-Ag_2S. Syn. of argentite. [M.A. **3**–338.]

Paratenorite. H. Strunz, Min. Tab., 1941, p. 95 (Paratenorit). Syn. of paramelaconite.

Patiñoite. M. C. Bandy, 1946. Mineralogía de Llallagua, Bolivia, La Paz, p. 57 (Patiñoíta). Provisional name for an undescribed mineral as yellow tetragonal crystals probably a phosphate or arsenate. Named after Simon Iturbi Patiño, who was the first to work the Llallagua mines. [M.A. **10**–9.]

Pennaite. D. Guimarães, 1948. Bol. Inst. Tecn. Indust. Minas Gerais, no. 6, p. 19 (pennaita), p. 59 (pennaite). Chloro-zircono-titanosilicate of Na, Ca, Fe, as minute triclinic crystals with aegirine in nepheline-rocks from Poços de Caldas, Brazil. Named after Dr. José

Moreira dos Santos Penna, director of the Instituto de Tecnologia Industrial. [M.A. **10**–510.]

Perplexite. P. Marshall, 1946. New Zealand Journ. Sci. Techn., Sect. B, vol. 28, p. 51. A compact zeolitic mineral not definitely identified in the groundmass of phonolitic rocks. [M.A. **10**–295.]

Phosphoralunogen. H. Strunz, Min. Tab., 1941, p. 135. Alunogen containing some P_2O_5 replacing SO_3, $Al_2[PO_3OH,(SO_4)_2].16H_2O$. The formula $Al_2(SO_4)_2(HPO_4).11\frac{1}{2}H_2O$, as originally given [M.A. **7**–470], however, points to meta-alunogen [M.A. **8**–278] rather than to alunogen.

Phosphormimetesit. H. Strunz, Min. Tab., 1941, p. 156. Mimetite with some arsenic replaced by phosphorus. Identified with campylite (Kampylit).

Picrophengite. A. N. Winchell, 1949. Amer. Min., vol. 34, p. 223. A hypothetical molecule $K_2MgAl_3(OH)_4Si_7AlO_{20}$, classed as a sub-species of muscovite. Compare ferrophengite (q.v.). [M.A. **10** 568.]

Plumbocolumbite. H. Strunz, Min. Tab., 1941, p. 108 (Plumbocolumbit). Syn. of plumboniobite (5th List).

Polyaugite. A. N. Winchell, 1949. Amer. Min., vol. 34, p. 224. To replace clinopyroxene as a species, rather than a group, name, with diopside, augite, jadeite as sub-species, excluding clinoenstatite and spodumene. [M.A. **10**–568.]

Potassium-cryolite. A. Duboin, 1892. Bull. Soc. Franç. Min., vol. 15, p. 191 (cryolithe potassique). P. Groth, Chem. Kryst., 1906, vol. 1, p. 416 (Kaliumkryolith). C. Brosset, Diss. Stockholm, 1942, p. 119 (potassium-cryolite). Artificial potassium fluo-aluminate near K_3AlF_6, analogous to cryolite. See Ammonium-cryolite. [M.A. **10**–16, 208.]

Protoenstatite. W. Büssem and C. Scheusterius, 1938. Wiss. Veröff. Siemens-Werken, vol. 17, p. 62 (Protoenstatit). Replacing the name metatalc (15th List) for an artificially produced modification of $MgSiO_3$.

Pseudo-kaliophilite. E. Gruner, 1935. Zeits. Anorg. Chem., vol. 224, p. 366 (Pseudokaliophilit). W. Borchert and J. Keidel, Heidelberger Beitr. Min. Petr., 1947, vol. 1, p. 11. $KAlSiO_4$ prepared by desulphurizing ultramarine in fused KCN, differing in X-ray pattern from kaliophilite. [M.A. **10**–364.]

Pulszkyite. J. S. Krenner, 1948. Schweiz. Min. Petr. Mitt., vol. 28, p. 707 (Pulszkyit). Sulphate of copper and magnesium as green hexagonal crystals with herrengrundite from Hungary (now Slovakia). Named after Ferencz Pulszky (1814–1897) formerly director of the Hungarian National Museum. [M.A. **10**–510.]

Pyrandine. B. W. Anderson, 1947. Journ. Gemmology, London, vol. 1, no. 2, p. 15. A contraction of pyrope and almandine for gem garnets of intermediate composition. (Cf. rhodolite, 2nd List; pyralmandite and pyralspite, 11th List.) [M.A. **10**–102.]

Rashleighite. A. Russell, 1948. Min. Mag., vol. 28, p. 353. Hydrous phosphate of aluminium, ferric iron, and copper, intermediate between turquoise and chalcosiderite, as blue to green encrustations from Cornwall. Named after the Cornish mineralogist Philip Rashleigh (1729–1811).

Renierite. J. F. Vaes, 1948. Ann. (Bull.) Soc. Géol. Belgique, vol. 72 (for 1948–9), p. B 19 (reniérite). Sulphide of Cu, Fe, Ge (7·75 %), Zn, As, near RS, tetrahedral-cubic, from Katanga. Named after Prof. Armand Renier, Director of the Geological Survey of Belgium. Near germanite. [M.A. **10**–454.]

Retgersite. C. Frondel and C. Palache, 1948. Program and Abstracts Min. Soc. Amer., 29th Annual Meeting, p. 6; Bull. Geol. Soc. Amer., vol. 59, p. 1323. Amer. Min., 1949, vol. 34, pp. 188, 276. Nickel sulphate hexahydrate, $NiSO_4.6H_2O$, tetragonal trapezohedral, long known as an artificial salt, has been recognized as a natural mineral at five localities, in association with morenosite (orthorhombic, $NiSO_4.7H_2O$). Named after Jan Willem Retgers (1856–1896), Dutch chemical crystallographer. [M.A. **10**–452, 506.]

Richetite. J. F. Vaes, 1947. Ann. (Bull.) Soc. Géol. Belgique, vol. 70, p. B 221. Hydrous (?) lead uranate as black monoclinic plates, from Katanga. Named in memory of Emile Richet, died 1939, chief geologist of the Union Minière du Haut-Katanga. [M.A. **10**–146.]

Rooseveltite. R. Herzenberg, 1946. Boletín Técnico, Fac. Nac. Ingeniería, Univ. Técnica, Oruro, no. 1, p. 10 (Rooseveltita). Bismuth arsenate, $BiAsO_4$, as a white coating on wood-tin from Santiaguillo, Bolivia. Named after Franklin Delano Roosevelt (1882–1945), President of the United States of America. [M.A. **10**–9.]

Sanmartinite. V. Angelelli and S. G. Gordon, 1948. Notulae Naturae, Acad. Sci. Philadelphia, no. 205. Zinc tungstate, near $ZnWO_4$ with small amounts of Fe, Mn, Ca, as minute monoclinic crystals very similar to wolframite; from San Martin, prov. San Luis, Argentina. Named from the locality, which in turn was named after the liberator José de San Martin (1778–1850). [M.A. **10**–353.]

Schmöllnitzit. R. Koechlin, Min. Taschenb. Wien. Min. Gesell., 2nd edit., 1928. Another form of szomolnokite (5th List), named from the locality in Slovakia: Szomolnok in Hungarian, Schmöllnitz in

German, and Smolník in Slovak. Evidently identical with ferropallidite, $FeSO_4.H_2O$ (3rd List).

Schuilingite. J. F. Vaes, 1947. Ann. (Bull.) Soc. Géol. Belgique, vol. 70, p. B 233. Carbonate of lead and copper as blue orthorhombic needles from Katanga. Named after H. J. Schuiling, geologist to the Union Minière du Haut-Katanga. [M.A. **10**–147.]

Scorzalite. W. T. Pecora and J. J. Fahey, 1947. Program and Abstracts, 28th Annual Meeting, Min. Soc. Amer., p. 18; Bull. Geol. Soc. Amer., vol. 58, p. 1216; Amer. Min., 1948, vol. 33, p. 205 (abstract); Mineração e Metalurgia, 1948, vol. 13, p. 53; Amer. Min., 1949, vol. 34, p. 83. Hydrous phosphate, $Al_2O_3.(Fe,Mg)O.P_2O_5.H_2O$, blue, monoclinic, differing from lazulite in having FeO in excess of MgO. From Divino, Brazil. Also from Custer, South Dakota (W. T. Pecora and J. J. Fahey, Amer. Min., 1949, vol. 34, p. 282). Named after Dr. Evaristo Pena Scorza, of the Mineral Survey of Brazil. [M.A. **10**–254, 456, 507.]

Selenio-siegenite. J. F. Vaes, 1947. Ann. (Bull.) Soc. Géol. Belgique, vol. 70, p. B 231 (Sélénio-Siegenite). A variety of siegenite containing Se 11·65, Te 3·80 %, $(Ni,Co,Cu)_3(S,Se,Te)_4$, from Katanga. [M.A. **10**–147.]

Selenio-vaesite. J. F. Vaes, 1947. Ann. (Bull.). Soc. Géol. Belgique, vol. 70, p. B 229 (Selenio-Vaesite), p. B 230 (Sélénio-Vaesite). A variety of vaesite (17th List) containing Se13·70–19·70 %, $Ni(S,Se)_2$, from Katanga. [M.A. **10**–146.]

Selenojarosite. A. E. Fersman and O. M. Shubnikova, Sputnik geokhimika i mineraloga, Acad. Sci. U.S.S.R., 1937, p. 197 (селен(о)ярозит). B. K. Breshenkov, Compt. Rend. (Doklady) Acad. Sci. URSS, 1946, vol. 52, p. 329 (selenojarosite). Jarosite with some SO_3 replaced by SeO_3 (0·20 %) from Altai and Kazakhstan. [M.A. **2**–113, **7**–6, **10**–248.]

Sengierite. J. F. Vaes and P. F. Kerr, 1949. Amer. Min., vol. 34, p. 109. (The name first appeared in newspapers in October 1948.) $2CuO.2UO_3V_2O_5.10H_2O$, as small green orthorhombic crystals from Katanga, Belgian Congo, Related to carnotite and tyuyamunite. Named after Edgard Sengier, Director of the Union Minière du Haut-Katanga. [M.A. **10**–507.]

Shishimskite. L. L. Shilin, 1940. Compt. Rend. (Doklady) Acad. Sci. URSS, 1940, vol. 28, p. 346. An ore mixture of perovskite, spinel, magnetite, and haematite from the Shishim Mts., Urals. [M.A. **8**–174.]

Souxite. R. Herzenberg, 1946. Boletín Técnico, Fac. Nac. Ingeniería, Univ. Técnica, Oruro, no. 1, p. 5. Hydrous tin oxide, $SnO_2.xH_2O$, as a

yellow colloidal powder from Potosí, Bolivia. Named after the late Louis Soux of Potosí. Compare Varlamoffite (q.v.). [M.A. **10**–9.]

Souzalite. W. T. Pecora and J. J. Fahey, 1947. Program and Abstracts, 28th Annual Meeting, Min. Soc. Amer., p. 18; Bull. Geol. Soc. Amer., vol. 58, p. 1216; Amer. Min., 1948, vol. 33, p. 205 (abstract); Mineração e Metalurgia, 1948, vol. 13, p. 53; Amer. Min., 1949, vol. 34, p. 83. Hydrous phosphate, $(Al,Fe)_2O_3.3(Mg,Fe)O.2P_2O_5.5H_2O$, green, fibrous, monoclinic (?); an alteration product of scorzalite (q.v.) from Divino, Brazil. Named after Dr. Antonio José Alves de Souza, formerly director of the Mineral Survey of Brazil. [M.A. **10**–254, 456, 507.]

Stannopalladinite. I. N. Maslenitzky, P. V. Faleev, and E. V. Iskyul, 1947. Doklady Acad. Sci. USSR, vol. 58, p. 1137 (станнопалладинит). Cubic alloy of tin and palladium, Pd_3Sn_2, with some Pt and Cu. [M.A. **10**–453.]

Stibioniobite. R. Koechlin, Min. Taschenb., Wien. Min. Gesell., 2nd edit., 1928, p. 60 (Stibioniobit). Syn. of stibiocolumbite (7th List).

Strontium-arsenapatite. H. Strunz, Min. Tab., 1941, p. 156 (Strontiumarsenapatit). Syn. of fermorite (5th List).

Studtite. J. F. Vaes, 1947. Ann. (Bull.) Soc. Géol. Belgique, vol. 70, p. B 223. Hydrous uranium carbonate as yellow flexible fibres, orthorhombic, from Katanga. Named after F. E. Studt, geologist, Tanganyika Concessions. [M.A. **10**–146.]

Swartzite. J. Axelrod, F. Grimaldi, C. Milton, and K. J. Murata, 1948, Program and Abstracts, Min. Soc. Amer., 29th Annual Meeting, p. 4; Bull. Geol. Soc. Amer., vol. 59, p. 1310; Amer. Min., 1949, vol. 34, p. 274. Hydrous calcium-magnesium-uranyl carbonate. $CaMgUO_2(CO_3)_3.nH_2O$, from Arizona. Named after Charles Kephart Swartz (1861–) Emeritus Professor of Geology, Johns Hopkins University. [M.A. **10**–452.]

Teshirogilite. Local name for ilmenorutile from Teshirogi, Fukushima-ken, Japan. T. Ito and K. Sakurai, Wada's Minerals of Japan, 3rd edition, 1947, vol. 1, p. 211 (figs. 3 and 4), p. 212 (two chemical analyses). [M.A. **10**–351.]

Thermitocorundum. R. L. Pevzner, 1947. Compt. Rend. (Doklady) Acad. Sci. URSS, vol. 55, p. 233. Artificial corundum prepared by the thermite process. [M.A. **10**–259.]

Thermitospinel. R. L. Pevzner, 1947. Compt. Rend. (Doklady) Acad. Sci. URSS, vol. 55, p. 233. Artificial spinel prepared by the thermite process. [M.A. **10**–259.]

Tinticite. B. Stringham, 1946. Amer. Min., vol. 31, p. 395. Hydrated basic ferric phosphate, $2FePO_4.Fe(OH)_3.3\frac{1}{2}H_2O$, as a compact creamy-white wall-coating in a limestone cave at Tintic, Utah. Named from the locality. [M.A. **10**–5.]

Titanspinel. F. Mogensen, 1943. See Ulvöspinel.

Ulvöspinel. F. Mogensen, 1943. Blad för Bergshandteringens Vänner, Stockholm, vol. 26, p. 135 (Ulvöspinellen), p. 134 (titanspinell). A titaniferous iron-ore in which a large excess of FeO is assumed to be present as Fe_2TiO_4 with a spinel structure. Named from the locality, Ulvö islands, Sweden. In a later paper, F. Mogensen, Geol. För. Förh. Stockholm, 1946, vol. 68, p. 578, these two names are replaced by 'ferro-ortho-titanate'. [M.A. **10**–6, 101.]

Vandendriesscheite. J. F. Vaes, 1947. Ann. (Bull.) Soc. Géol. Belgique, vol. 70, p. B 217. Hydrous lead uranate as amber-orange orthorhombic crystals resembling fourmarierite, from Katanga. Named in memory of Adrien Vandendriessche (1914–40) of Ghent. [M.A. **10**–146, 255.]

Varlamoffite. R. De Dycker, 1947. H. Buttgenbach, Les minéraux de Belgique et du Congo Belge, Liège, 1947, p. 182. N. Varlamoff, Ann. (Bull.) Soc. Géol. Belgique, 1948, vol. 71 (for 1947–8), pp. B 224, B 226, B 232; ibid., 1948, vol. 72 (for 1948–9), p. B 41. Metastannic acid, H_2SnO_3, as a yellow earthy material from alteration of stannite, from Kalima, Belgian Congo. Named after Nicolas Varlamoff, mining engineer, Belgian Congo, who found the mineral. Compare Souxite (q.v.). [M.A. **10**–354, 454, 495.]

Wathlingenite. [C. Prager, 1923]. Student's index to the collection of minerals, British Museum, 27 edit., 1936, p. 37 (Wathlingite, Wathlingenite), from dealers' labels in 1923 and 1930. Described as $CaSO_4$. $MgSO_4.H_2O$, from salt deposits at Wathlingen, near Celle in Hanover. Probably a mixture of anhydrite and kieserite.

Weddellite. C. Frondel and E. L. Prien, 1942. Science (Amer. Assoc. Adv. Sci.), vol. 95, p. 431; E. L. Prien and C. Frondel, Journ. Urology, Baltimore, 1947, vol. 57, p. 965. Calcium oxalate, CaC_2O_4. $2H_2O$, described by F. A. Bannister and M. H. Hey [M.A. **6**–341] in deep-sea deposits from the Weddell Sea, Antarctic, and also present in urinary calculi. [M.A. **10**–40, 215.]

Wisaksonite. J. H. Druif, 1948. Mededeel. Algem. Proefstation Landbouw. (Communic. General Agricultural Experiment Station), Buitenzorg, Java, 1948, no. 69, p. 8. Clear green metamict zircon as minute crystals in river sands from Celebes. Named after Wisaksono Wirjodihardjo, of the Institute for Soil Reserach, Buitenzorg. [Metamict

zircon has been previously referred to as α-zircon, meta-zircon, pseudo-zircon, zirconoid, low-zircon, low-density zircon. Min. Mag. **14**–48, M.A. **7**–130–1, 522–3, **8**–123.] [M.A. **10**–455.]

Yttroniobite. H. Strunz, Min. Tab., 1941, p. 107 (Yttroniobit). Syn. of yttrocolumbite.

Zinc-aragonite. A. K. Boldyrev, Kurs opisatelnoi mineralogii, Leningrad, 1928, pt. 2, p. 202 (цинкарагонит). H. Strunz, Min. Tab., 1941, p. 118 (Zinkaragonit). Syn. of nicholsonite (6th List).

SYSTEMATIC CLASSIFICATION OF NEW MINERALS[1]

Elements

Stannopalladinite, Pd_3Sn_2.

Sulphides, etc.

Achavalite, FeSe.
Frohbergite, $FeTe_2$.
Csiklovaite, Bi_2TeS_2.
Selenio-vaesite, $Ni(S,Se)_2$.
Selenio-siegenite, $(Ni,Co,Cu)_3(S,Se,Te)_4$.
Parajamesonite, $4PbS.FeS.3Sb_2S_3$.
Dervillite, S, Sb, Pb.
Renierite, S, Cu, Fe, Ge, &c.

Haloids

Paragearksutite, $4CaF_2.4Al(F,OH)_3.3H_2O$.
Bromcarnallite.
Ammonium-cryolite.

Oxides

Monteponite, CdO.
Nigerite, $(Zn,Mg,Fe'')(Sn,Zn)_2(Al,Fe''')_{12}O_{22}(OH)_2$.

Hydroxides

Souxite, $SnO_2.xH_2O$.
Varlamoffite, H_2SnO_3.
Hydrohausmannite.
Paraschoepite, $5UO_3.9\frac{1}{2}H_2O$.
Epiianthinite, $UO_3.xH_2O$.
Merumite, Cr_2O_3, Al_2O_3, H_2O.

Carbonates

Fairchildite, $K_2CO_3.CaCO_3$.
Buetschliite, $3K_2CO_3.2CaCO_3.6H_2O$.
Andersonite, $Na_2CaUO_2(CO_3)_3.nH_2O$.
Bayleyite, $Mg_2UO_2(CO_3)_3.nH_2O$.
Swartzite, $CaMgUO_2(CO_3)_3.nH_2O$.
Diderichite, U, H_2O.
Studtite, U, H_2O.
Schuilingite, Pb, Cu.

Uranates

Aldanite, ThO_2, UO_2, UO_3, PbO.
Billietite, Ba, H_2O.
Masuyite, Pb, H_2O.
Richetite, Pb, H_2O?
Sengierite, $2CaO.2UO_3.V_2O_5.10H_2O$.
Vandendriesscheite, Pb, H_2O.

Sulphates

Retgersite, $NiSO_4.6H_2O$.
Basaluminite, $2Al_2O_3.SO_3.10H_2O$.
Hydro-basaluminite.
Koktaite, $(NH_4)_2Ca(SO_4)_2.H_2O$.
Aluminocopiapite.
Barytoanglesite.
Pulszkyite, Cu, Mg.

Tungstates

Sanmartinite, $ZnWO_4$.
Anthoinite, $Al_2O_3.2WO_3.3H_2O$.
Calcowulfenite.
Molybdoscheelite.

Phosphates, etc.

Rooseveltite, $BiAsO_4$.
Scorzalite, $Al_2O_3.(Fe,Mg)O.P_2O_5.H_2O$.
Souzalite, $(Al,Fe)_2O_3.3(Mg,Fe)O.2P_2O_5.5H_2O$.
Tinticite, $2FePO_4.Fe(OH)_3.3\frac{1}{2}H_2O$.
Llallagualite.
Patiñoite.
Rashleighite.

[1] Only selected names given in the preceding alphabetical list are here included.

NIOBATES

Fersmite, $CaNb_2O_5$, &c.
Nuevite, Nb, Ti, Yt, Fe.

ANTIMONATES

Jujuyite, Sb, Fe.

TELLURITES

Dunhamite, $PbO.TeO_2$?

BORATES

Johachidolite,
$'H_6Na_2Ca_3Al_4F_5B_6O_{20}.'$

SILICATES

Bredigite, α'-Ca_2SiO_4.
Manganese-anorthite.
Beryllium-felspar.
Cymrite, $BaAlSi_3O_8(OH)$.
Harkerite, Ca, B, CO_3, SiO_2
Bowleyite,
$3(Ca,Be)O.2Al_2O_3.3SiO_2.2H_2O$
$+n(Li,Na)_2O$.
Duplexite,
$6CaO.4BeO.Al_2O_3.14SiO_2.2H_2O$.
Eulite (orthopyroxene).
Lime-bronzite.
Ferroactinolite, &c.
Heikkolite (alkali-amphibole).
Pyrandine (garnet).
Ammonium-mica.
Mavinite (mica).
Loughlinite, $MgSi_2O_5.aq$.
Giannettite, Si, Ti, Zr, Cl, Ca, Na, Mn.
Pennaite, Si, Ti, Zr, Cl, Na, Ca, Fe.
Fluor-chondrodite.
Fluor-norbergite.
Magnesium-cordierite.
Manganese-cordierite.
Apoanalcite, $NaAl(Al,Si)SiO_6.1\frac{1}{2}H_2O$.
Manganonatrolite.
Falkenstenite (zeolite).
Kurtzite (zeolite).
Perplexite (zeolite).
Ferrimontmorillonite.
Lembergite (clay).

HYDROCARBONS

Weddellite, $CaC_2O_4.2H_2O$.
Calclacite, $CaCl_2.Ca(C_2H_3O_2)_2.10H_2O$.
Harbolite.

INDEX TO VOL. XXVIII

[See also List of new mineral names (p. 722). Only the main items are here indexed; for fuller details see Index to Mineralogical Abstracts, vol. 10.]

Adams (F. D.), obituary, 176
Adamson (O.), exhibit, lxiv
Ahrens (L. H.), Radiogenic strontium, 277
Aloisi (P.), obituary, 177
Aminoff (G.), obituary, 177
Amphibole in Tiree marble, 230
Anatase in fireclay, 244; in kaolin, 492
Andersen (O.), obituary, 178
Anderson (C.), obituary, 178
Andrews (K. W.), Artificial melilites, X-ray, 374
Anhydrite, Yorks., 626
— -dolomite-rock, 637
— -magnesite-rock, 642
Ankerite, N. England, anal., 53
Annual Report, xliii, lviii, lxxiv
Arnold-Bemrose (H. H.), obituary, 179
Artificial minerals in boiler deposits, 359

Balance sheet, xlvi, lx, lxxvi
Bannister (F. A.), Whitlockite, Algeria, 29
— exhibit, xlv
— X-ray determinations, 343
— Hey (M. H.), & Stadler (H. P.), Nigerite, 129
— & Hutchinson (G. E.), Identity of minervite and palmerite with taranakite, 31
— *v.* Dunham (K. C.), 338; Smith (W. C.), 676
Barrett (L. R.) *v.* Gad (G. M.), 587
Bayley (W. S.), obituary, 179
Beard (E. H.), exhibit, lxiv
Bemrose (H. H.), obituary, 179
Benallt mine, Wales, 108, 343, 676, xxxvii
Bennett (H.), analysis by, 29
Bentonite, reaction with amines, 598
Bergt (W. A.), obituary, 180
Berkeley (R. T. M. R.), obituary, 180
Berman (H.), obituary, 181
Berry (L. G.) *v.* Peacock (M. A.), 1
Bibliographies, regional, 303
Billiet (V. L.), obituary, 182
Biographical notices, 175
Biotite, decomposition in soil, 693
Blake (G. S.), obituary, 182
Blyth (F. G. H.), Pyroxene, Shropshire, 380
Bodenbender (W.), obituary, 183
Boeris (G.), obituary, 183
Boiler deposits, minerals, 359
Bowman (H. L.), obituary, 184
Bragg (W. H.), obituary, 185
Bredigite, 255
Brindley (G. W.) & Goodyear (J.), Halloysite & metahalloysite, I, 407
— & Robinson (K.), Anatase in fireclay, 244
— — Halloysite & metahalloysite, II, 393
— — & Goodyear (J.), Halloysite & metahalloysite, III, 423
British minerals, xxxvii, xxxix, lii, lv, lxxi, 45, 53, 90, 108, 151, 173, 230, 244, 248, 255, 272, 308, 338, 353, 380, 505, 517, 534, 563, 621, 676, 693, 704, 714
British Museum, exhibits, xxxix, xl, lii
Brøgger (W. C.), obituary, 186
Bromehead (C. E. N.), Flavus or blavus, 104
— Ships' loadstones, 429
Brown (E. E. S.), exhibit, lii
Bye-laws, vii, lxv, lxvi, lxix–lxxi

Cahn (L.), obituary, 187
Caillère (S.) & Hénin (S.), Alteration of montmorillonite to mica, 606
— — Alteration of montmorillonite to chlorite, 612
Cassiterite, Nigeria, 126; Wherry mine, 528; artificial, 111
Celestine, Yorks., 627
Chalybite, N. England, anal., 53
Chrysoberyl, Nigeria, 126
Chrysotile, thermal decomposition, 333
Claringbull (G. F.), exhibit, lxiv, xlv
— *v.* Smith (W. C.), 108; Dunham (K. C.), 338
Clark (L. M.), Minerals in boiler deposits, 359
Clay, Egypt, 587
Clay Minerals Group, xl, xliii, lii, liii, lviii, lxvii, lxxiv
Clerici (E.), obituary, 188
Cleveland dike, crystal-size, 563
Clinozoisite, Wicklow, 505

Collophane, Durham, 340
Cordierite, iron-, 547
Crystallization of basaltic magma, 557
Crystal-size in dikes, 557
Cullis (C. G.), obituary, 188
Cuspidine, Skye, 90; Ireland, 157
Cymrite, 676

D'Achiardi (G.), obituary, 189
Davison (E. H.), obituary, 189
Deans (T.), exhibit, xliv
Dickite, Durham, 338; Witwatersrand, 582
Diorite, delimitation, 447
Dittler (E.), obituary, 190
Dollar (A. T. J.), Refractive index comparator, 438
Dolomite, Yorks., 628; siliceous, metamorphism, 272
Donnelly (H. F.) *v.* Nagelschmidt (G.), 492
Dunham (K. C.), Durham excursion, 45
— Claringbull (G. F.), & Bannister (F. A.), Dickite & collophane, Durham, 338
— & Hollingworth (S. E.), Excursion to Penrith, 248
— *v.* Smythe (J. A.), 53
Durham excursion, 45

Ellis (S. E.), Delimitation of diorite, gabbro, &c., 447
Endellite = halloysite, 36
English (G. L.), obituary, 190
Epidote-clinozoisite series, 513
Eskdale boring, Yorks., 621
Eulite, 165
Evaporites, Eskdale, Yorks., 621
Excursion to Durham, 45
— Penrith, 248

Felspar, refractive indices, 367
Ferroaugite, subcalcic, 159
Ferromangandolomite, 65
Fersman (A. E.), obituary, 191
Fireclay, anatase in, 244
Fleming (J. M.), Mica as a munition of war, xxxix
Flett (J. S.), obituary, 192
Foote (H. W.), obituary, 193
Ford (W. E.), obituary, 193
Frankel (J. J.), Artificial cassiterite, 111
— Dickite, Witwatersrand, 582

Gabbro, delimitation, 447
Gad (G. M.) & Barrett (L. R.), Egyptian clays, 587
Gahnite, Nigeria, 126, 136
Game (P. M.), Plagioclase, Kenya, 682
Ganophyllite, Wales, opt., 343
Geochemistry of radiogenic strontium, 277; of zinc, 575
Gibbs (A. M.), obituary, 194
Ginori-Conti (P.), obituary, 194
Goethe's interest in British mineralogy, 534
Goldschmidt (V. M.), obituary, 195
Goodyear (J.) *v.* Brindley (G. W.), 407, 423
Guild (F. N.), obituary, 196
Gypsum, Yorks., 628

Hackman (V. A.), obituary, 196
Halite, Yorks., 629
— -anhydrite-rock, 633
Hallimond (A. F.), Pyroxenes, &c., in Tiree marble, 230
— exhibit, lxxi
— & Taylor (E. W.), polarizing microscope, 96, 296
Halloysite minerals, nomenclature, 36
Halloysite & metahalloysite, 393, 407, 423
Harker (A.), obituary, 197
Harkerite, lxxi
Harry (W. T.) & Patterson (E. M.), Dolomite, Banff, 714
Hart (R.) *v.* Mackenzie (R. C.), 704
Harvey (C. O.) analyses by, 230, 338
Hénin (S.) *v.* Caillère (S.), 606, 612
Hennig (J.), Goethe's interest in British mineralogy, 534
Hey (M. H.) & Bannister (F. A.), Thermal decomposition of chrysotile, 333
— *v.* Smith (W. C.), 676
Hibsch (J. E.), obituary, 198
Himmelbauer (A.), obituary, 199
Historical, 104, 429, 517, 534
Hitchen (C. S.), exhibit, xxxix
Hodge-Smith (T.), obituary, 199
Högbom (A. G.), obituary, 200
Holland (T. H.), obituary, 201
Hollingworth (S. E.) *v.* Dunham (K. C.), 248
Honess (A. P.), obituary, 202
Hutchinson (G. E.) *v.* Bannister (F. A.), 31

Igneous-rocks, classification, 447, 688; silica percentage, 688
Illite, Aberdeenshire, 704
Interferometry of micas, 137, 146
Iron-cordierite in blast-furnace, 547

Jacobson (R.) & Webb (J. S.), Nigerite, 118
Johnson (F. B.), exhibit, lxviii

Johnston (R. W.), Clinozoisite, Wicklow, 505
Jones (T. G.), exhibit, xxxviii
Jordan (J. W.), Alteration of properties of bentonite with amines, 598

Kalsilite in blast-furnace, 75
Kaolin, anatase in, 492
Kennedy (W. Q.), Scottish mica, xxxix
Koechlin (R. I.), obituary, 202
Koenigsberger (J. G.), obituary, 202
Kolbeck (F.), obituary, 203
Kolderup (C. F.), obituary, 204
Kreutz (S.), obituary, 204
Krieger (P.), obituary, 204
Kulik (L. A.), obituary, 205
Kurnakov (N. S.), obituary, 205

Larnite, from inversion of bredigite, 260
Levinson-Lessing (F. Y.), obituary, 206
Lincio (G.), obituary, 207
Lindgren (W.), obituary, 208
Loadstones, ships', 429
Lonsdale (K.), Extinction in X-ray crystallography, 14

MacEwan (D. M. C.), Nomenclature of halloysite minerals, 36
Mackenzie (R. C.), Walker (G. F.), & Hart (R.), Illite, Ballater, 704
Magnesite, Yorks., 630
Marble, Tiree, 230
Marsh (E. S.), exhibit, lxiv
Mathias (M.), Olivine from South African melilite-basalts, 486
Maufe (H. B.), obituary, 209
Melilite, artificial, X-ray, 374
Melmore (S.), Densest and least dense packing of equal spheres, 479
Members, list of, xiii
Metahalloysite, 37, 393, 407, 423
Metamorphism of siliceous dolomite, 272
Meteorite collections, catalogues, 471
Mica, interferometry, 137; as a munition of war, xxxix; in Tiree marble, 230
Microscope, polarizing, 96, 296
Microscopy, phase-contrast, 103, 384
Miers (H. A.), obituary, 209
Millosevich (F.), obituary, 209
Minervite = taranakite, 31
Molengraaff (G. A. F.), obituary, 210
Morcom (A. J.) *v.* Nagelschmidt (G.), 492
Morozewicz (J. M.), obituary, 210
Morris (P. G.) *v.* Tolansky (S.), 137, 146

Nagelschmidt (G.), Donnelly (H. F.), & Morcom (A. J.), Anatase in kaolin, 492
Neumann (H.), Geochemistry of zinc, 575
Nigerite, 118, 129
Nikitin (V. V.), obituary
Nockolds (S. R.), Tilleyite, Ireland, 151
Nováček (R.), obituary, 212

Oates (F.), obituary, 212
Obituaries, 175
Oliveira (E. P. de), obituary, 212
Olivine in melilite-basalt, South Africa, 486

Packing of equal spheres, 479
Palmerite = taranakite, 31
Partridge (F. C.), obituary, 213
Patterson (E. M.) *v.* Harry (W. T.), 714
Peacock (M. A.) & Berry (L. G.), Polybasite and pearceite, 1
Pearceite, cryst. X-ray, 1
Peck (A. B.), obituary, 213
Pegmatite, Nigeria, 120
Penrith excursion, 248
Petrology of evaporites, 621
Phase-contrast microscopy, 103, 384
Pigeonite, definition, 164
Pinnoite, space-group
Plagioclase, Kenya, 682
Platnauer (H. M.), obituary, 214
Poldervaart (A.), Subcalcic ferro-augite, 159
— Orthopyroxene & pigeonite, 164
Pollard (W.), obituary, 214
Polybasite, cryst. X-ray, 1
Polyhalite, Yorks., 631
— -rocks, 646
Pope (W. J.), obituary, 214
Pratt (J. H.), obituary, 215
Pseudomorphs in evaporites, 649, 652
Pyrophanite, Wales, 108
Pyroxene, nomenclature, 159, 164; Shropshire, 380; in Tiree marble, 230

Radiogenic strontium, 277
Raisin (C. A.), obituary, 216
Rashleighite, 353
Refractive index comparator, 438; determination, 367
Richardson (H. M.) & Rigby (G. R.), Iron-cordierite in blast-furnace, 547
Rigby (G. R.) & Richardson (H. M.), Kalsilite in blast-furnace, 75
Riley (D. P.) & Segnit (E. R.), Silico-carnotite in slag, 496
Rimann (E.), obituary, 216

Robins (O.), Determination of refractive indices of felspar, 367
Robinson (K.) *v.* Brindley (G. W.), 244, 393, 423
Rocks, delimitation of diorite, gabbro, &c., 447
Rogers (A. W.), obituary, 216
Ronnebeck (R. H.) *v.* Vickers (A. E. J.), lvi
Rose (W. C. C.), Scottish mica, xxxix
Rosický (V.), obituary, 217
Russell (A.), Rashleighite, 353
— Wherry mine, Penzance, 517
— exhibits, xxxvii, xlv, lxxii
Rubidium, radioactive change to strontium, 277

Sabine (P. A.), exhibit, lxvi
Seager (A. F.), exhibit, xli
Segnit (E. R.) *v.* Riley (D. P.), 496
Silica % in igneous rocks, 688
Silicocarnotite, 496
Sillimanite-quartz-rocks, Nigeria, 121
Šimek (A.), obituary, 218
Simpson (E. S.), obituary, 218
Slag minerals, 75, 111, 255, 496, 547
Slavík (F.), exhibit, xlv
Slavíková (L.), obituary, 219
Smith (W. C.), Ganophyllite, Benallt mine, 343
— exhibit, xxxvii
— Bannister (F. A.), & Hey (M. H.), Cymrite, 676
— & Claringbull (G. F.), Pyrophanite, Benallt mine, 108
Smithson (F.), Phase-contrast microscopy, 384
Smythe (J. A.), Ullmannite, Durham, 173
— analysis by, 353
— & Dunham (K. C.), Ankerite and dolomite, 53
Spencer (L. J.), Biographical notices, 175
— Topographical mineralogies, 303
— Catalogues of meteorite collections, 471
— New mineral names, 722
— exhibit, xxxix
Stadler (H. P.), Pinnoite, 26
— *v.* Bannister (F. A.), 129
Steiger (G.), obituary, 220
Stewart (F. H.), Petrology of evaporites, Yorks., 621
Strontium, radiogenic, 277
Suess (F. E.), obituary, 220
Sulphur, native, Yorks., 632
Swift (M. J.), obituary, 221

Talc in evaporites, 633
Taranakite, 31
Tarr (W. A.), obituary, 221
Taylor (E. W.), Scales of hardness, 713
— *v.* Hallimond (A. F.), 96, 296
Thomson (J. Ellis), obituary, 221
Tilley (C. E.), Cuspidine, Skye, 90
— Metamorphism of siliceous dolomite, 272
— exhibit, harkerite, lxxi
— & Vincent (H. C. G.), Bredigite, Scawt Hill & in slags, 255
Tilleyite, Ireland, 151
Tolansky (S.) & Morris (P. G.), Interferometry of micas, 137
— — Synthetic mica, 146
Topographical mineralogies, 303
Turquoise-chalcosiderite group, 353

Ullmannite, Durham, 173
Ulrich (F.), obituary, 222

Vandendriessch (A.), obituary, 223
Varley (E. R.), German mica industry, xxxix
Vermiculite, 700
Vernadsky (V. I.), obituary, 223
Vickers (A. E. J.) & Ronnebeck (R. H.), exhibit, lvi
Vincent (H. C. G.), analyses by, 90, 151
— *v.* Tilley (C. E.), 255

Walker (G. F.), Decomposition of biotite in soil, 693
— *v.* Mackenzie (R. C.), 704
Walker (T. L.), obituary, 224
Walsh (R. C.), exhibit, lii
Watts (W. W.), obituary, 225
Webb (J. S.) *v.* Jacobson (R.), 118
Webster (R.), exhibit, lxvi
Wells (A. K.), Silica % in igneous-rock classification, 688
Wells (R. C.), obituary, 226
Wherry mine, Penzance, 517
Whitlockite, Algeria, 29
Whitten (D. G. A.), exhibit, lv
Winkler (H. G. F.), Crystallization of basaltic magma, crystal-size in dikes, 557
Wolff (J. E.), obituary, 227

X-ray extinction, 14

Zemyatchensky (P. A.), obituary, 228
Zimányi (K.), obituary, 228
Zinc, geochemistry, 575

PRINTED IN GREAT BRITAIN
AT THE UNIVERSITY PRESS, OXFORD
BY CHARLES BATEY, PRINTER TO THE UNIVERSITY

DATE DUE

PERIODICALS MAR 2 '71

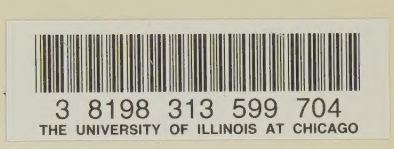
[redacted]

UIC MAR 23 '88

RET'D PER MAR 2 3 1988

PERIODICALS MUST BE RETURNED
TO PERIODICALS DESK ONLY.

GAYLORD PRINTED IN U.S.A.


3 8198 313 599 704
THE UNIVERSITY OF ILLINOIS AT CHICAGO